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ABSTRACT

The permeability ($\overline{P}$) and diffusion coefficient (D) of the gases H_2, Ar, Kr and Xe have been measured in certain elastomer materials of interest to the FFTF/CRBRP Cover Seal Program. These elastomers include Buna N, Buna S, Butyl Rubber, ethylene-propylene polyacrylic, polyurethane and silicone. Measurements were made over the temperature range 100 to 300°F. Data for the permeability and diffusion coefficient for these gases in the above elastomer materials are given. The method used also yields data for the solubility of gas in the elastomer; however, these data are less precise than data for $\overline{P}$ and D.

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CONTENTS

Page

I. Objective 5
A. Goal 5
B. Purpose 5
C. Technical Approach 5
II. Description of Test 6
A. Description of Test Article 6
B. Test Environment 6
C. Measurements Performed 6
D. Instruments and Equipment 7
III. Results 8
A. Data Analysis 8
B. Typical Calculation 10
C. Data Precision 11
1. Permeability 11
2. Diffusion Coefficient 12
3. Solubility 12
D. Test Specimens Examined 13
E. Test Results 13
1. Buna N 13
2. Buna S 14
3. Butyl Rubber 14
4. Ethylene-Propylene 14
5. Polyacrylic 15
6. Silicone 15
7. Urethane 15
IV. Summary of Results 16
V. References 18

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TABLES

Page

1. Solubility of Gases in Elastomeric Materials. 19
2. Diffusion Coefficient (D) of H_2, Ar, Kr and Xe in Buna N Elastomers. 20
3. Diffusion Coefficient (D) of H_2, Ar, Kr and Xe in Buna S Elastomers. 21
4. Diffusion Coefficient (D) of H_2, Ar, Kr and Xe in Butyl Rubber. 22
5. Diffusion Coefficient (D) of H_2, Ar, Kr and Xe in EPR Elastomers 23
6. Diffusion Coefficient (D) of H_2, Ar, Kr and Xe in Polyacrylic Elastomers. 24
7. Diffusion Coefficient (D) of H_2, Ar, Kr and Xe in Silicone Elastomers 25
8. Diffusion Coefficient (D) of H_2, Ar, Kr and Xe in Urethane Elastomers. 26
9. Comparison of Permeability ($\overline{P}$) of H_2, Ar, Kr and Xe Through Elastomers at 150°F. 27
10. Permeability of Hydrogen in Buna S, Butyl, and Silicone Elastomers, Compared With Literature Data. 28

FIGURES

1. Schematic Diagram of Gas Permeation Apparatus 29
2. Pictorial View of Gas Permeation Apparatus. 30
3. Typical Plot of Volume Flow vs Time for Diffusing Gas at Constant Temperature 31
4. Permeation Rate of Hydrogen Through Ethylene-Propylene Elastomer (Parker Seal No. 529 at 202°F). 32
5. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Buna N Rubber, Greene Tweed Co., Compound 969. 33
6. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Minnesota Rubber Co., Buna N, Compound 366Y 34

FIGURES

Page

7. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Minnesota Buna N (366Y, Batch 982, 2nd Lot) 35
8. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Buna N Rubber, Parker Seal Co., Compound N741 36
9. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Minnesota Rubber Co., Buna S Compound 480DR 37
10. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Parker Seal Buna S (G244) 38
11. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Parker Seal Butyl Rubber (B318-70) 39
12. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Ethylene-Propylene Rubber, Greene Tweed Co., Compound 972 40
13. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Ethylene-Propylene Rubber, Minnesota Rubber Co., Compound 559N 41
14. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Parker Seal EPR E529) 42
15. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Ethylene-Propylene Rubber, Parker Seal Co., Compound E692 43
16. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Minnesota Rubber Co., Polyacrylic (335GA) 44
17. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Parker Seal Polyacrylic (A607) 45
18. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Silicone Rubber, Greene Tweed Co., Compound 407 46
19. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Silicone Rubber, Minnesota Rubber Co., Compound 71417 47
20. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Silicone Rubber, Parker Seal Co., Compound S684 48
21. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Urethane Rubber, Greene Tweed Co., Compound 379 49
22. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Urethane Rubber, Minnesota Rubber Co., Compound FX522 50
23. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Parker Seal Urethane (P642) 51
24. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr and Xe for Urethane Rubber, Parker Seal Co., Compound (P648) 52

I. OBJECTIVE

A. GOAL

The goal of these studies is to determine the permeability $\overline{P}$, diffusion coefficient D, and solubility σ of certain gases such as hydrogen, argon, krypton and xenon in selected elastomers in the temperature range 100 to 300°F. The initial tests are aimed at confirming the seal material selection for the FFTF application, subsequent tests will be made to support the CRBRP Program.

B. PURPOSE

A large number of elastomer seals will be required in the FFTF/CRBRP systems to prevent significant gas leakage through the many penetrations. Measurement of the permeability is necessary in order to determine the amount of radioactive gases which can reach the building atmosphere by permeation alone. Solubility data are necessary in order to predict radiation damage to the elastomer due to presence of dissolved radiosiotopes of these gases.

C. TECHNICAL APPROACH

The apparatus used for determining the solubility and permeability of the above gases in selected elastomers is shown schematically in Figure 1 and pictorially in Figure 2. It consists of two interconnected chambers with the elastomer under test firmly affixed in the interconnection, thus creating two gas chambers separated by the elastomer. One chamber was filled with the test gas to slightly more than one atmosphere pressure. The other chamber was filled with helium to a similar pressure. The partial pressure of the test gas in the helium chamber was determined periodically by a gas chromatograph. Using these measurements in conjunction with the time-lag technique (References 1 and 2), the solubility and permeability of the gas in the elastomer was calculated.

II. DESCRIPTION OF TEST

A. DESCRIPTION OF TEST ARTICLE

The test specimens consisted of a disc of the selected elastomer, firmly affixed in the interconnection between the two chambers, with a known cross-sectional area exposed to the gas. Two and one half inch diameter discs nominally 0.080 inches thick were used for the tests.

B. TEST ENVIRONMENT

One side of the elastomer was exposed to the test gas at slightly above atmospheric pressure. The other side of the elastomer was exposed to helium at a similar pressure. The assembly was contained in an oven maintained at test temperatures specific for the particular elastomer.

C. MEASUREMENTS PERFORMED

The temperature of the elastomer under test was measured and maintained at a specified temperature within a tolerance of ±3°F for temperatures up to 200°F. Temperature tolerances for temperatures greater than 200°F was ±4°F. Internal pressure of the chambers was maintained at several mm Hg gauge and was measured by simple mercury manometers. Precision was held at ±1/2 mm Hg. The total pressure in each chamber was calculated using the barometric pressure during the test. The partial pressure of the test gas was determined chromatographically with a precision of ±15% for the low pressure chamber and ±2% for the high pressure chamber. The thickness of the test specimen was determined with a micrometer to ±0.002 inch. The cross-sectional area of the elastomer membrane was calculated from the diameter as measured by a micrometer to ±0.001 inch. Chamber volume was determined with water to ±1/2 mℓ.

D. INSTRUMENTS AND EQUIPMENT

The test apparatus used for these measurements is similar to the apparatus previously employed to measure the solubility and permeability of xenon and nitrogen in silicone, ethylene-propylene and urethane elastomers at temperatures up to 200°F. A schematic drawing of this apparatus is shown in Figure 1. This apparatus, with the oven cover removed, is also shown pictorially in Figure 2. The exposed view shows the two halves of the stainless steel permeation chambers. Located between the two halves of the permeation chambers is a double faced flange which holds the elastomer sample sealed and secured by flanges.

This entire apparatus is enclosed within a thermostatically controlled oven held to within ±3°F of the specified temperature. The temperature of the elastomer under test is measured by use of stainless steel clad Chromel-Alumel junctions in contact with each side of the specimen. The emf's of these calibrated junctions, relative to a reference junction at 32°F, are measured with a Rubicon Model 2745 potentiometer and are monitored continuously during a run with a Hewlett-Packard Model 7100B recording potentiometer.

Pressure in the permeation chamber throughout the time of the outgassing procedure is determined with a National Research Corporation thermocouple gage. Pressures in each of the permeation chambers in the course of a run are made with mercury manometers separated from the apparatus by mercury traps.

One side of this dual chamber apparatus is filled to a specified pressure with the gas or mixture of gases for which the permeabilities and solubilities are desired. The other chamber, separated by the elastomer under test, is filled with reactor grade helium. Analyses were performed at periodic intervals by taking small aliquot samples (1.00 cc) from the helium chamber using a Carle gas sampling valve. The gas sample was then analyzed with a Varian-Aerograph Model 1532-2B gas chromatograph to determine the partial pressure of the diffusant gas in the chamber.

The chromatograph was calibrated against standardized mixtures of the diffusant gas species mixed with reactor grade helium. Several such mixtures were used; the concentrations of gases were chosen to bracket the concentration range of the gases to be measured in the permeation/solubility tests. This yielded a calibration curve from which the concentration of the diffusant gas in the chamber could be determined. The gas chromatograph was periodically compared against this calibration curve to maintain its accuracy.

III. RESULTS

A. DATA ANALYSIS

The tests were designed to measure permeation of the test gas through an elastomer diaphram under the conditions of total zero pressure differential since the pressure in the receiving chamber (helium) was adjusted to approximately the pressure existing in the adjacent chamber. Thus the driving force for permeation of gas through the elastomer membrane was the difference in partial pressure of the test gas between the two chambers. Initially, the partial pressure of the test gas in the sampling chamber was near zero, the primary component being reactor grade helium. This initial concentration was established experimentally by gas chromatographic analysis at "time zero." The periodic sampling and analysis of the gas (gases) in the helium chamber yielded the concentration or partial pressure in this chamber whose volume and total pressure was known. Subsequently, the mass rate of flow, in standard cubic centimeters per unit time through an elastomer of known geometry i.e., cross-sectional area and thickness, under the driving force of a known partial pressure was established for a specified temperature.

Treatment of this mass flow per unit time data yields the permeability, $\bar{P}$, the diffusion coefficient, D, and the solubility of the gas, σ, in the elastomer. As an illustration, consider a typical example of mass flow versus time such as shown in Figure 3. When $t \ll L$, the concentration of test gas in the sampling chamber is near zero. A large fraction of the gas entering the elastomer remains therein until the elastomer

approaches saturation as these particular conditions of temperature and partial pressure. Finally at some point where t > L a steady state condition is reached where the mass or standard volume flow per unit time is constant, i.e., the gas flow into the membrane equals the flow from the membrane, the membrane being saturated with the gas. The permeability, $\overline{P}$, was calculated from this limiting slope of dV/dt by the relationship

$$\overline{P} = \frac{cm^3/sec \times d}{A\Delta P_a} \qquad \ldots(1)$$

where d is the thickness of the elastomer and A is its cross-sectional area and ΔP_a is the pressure differential or driving force of diffusant gas across the elastomer membrane.

Extrapolation of this limiting slope back to zero mass concentration of the diffusing gas in sampling chamber yields the lag time, L. This lag time L represents the time required for the elastomer to become saturated with the diffusant gas under the idealized conditions that all the gas entering the elastomer (at a rate dV/dt) remains in the elastomer until it is saturated at which time the gas exiting the membrane equals the gas entering the membrane = dV/dt.

The diffusion coefficient, D, can be calculated from the time lag, L, from the relationship

$$D = \frac{d^2}{6L} \quad . \qquad \ldots(2)$$

Thus, having P and D experimentally, the solubility, σ, may be calculated as follows:

$$\sigma = \frac{\overline{P}\ 76\ cm\ Hg/atm}{D} \qquad \ldots(3)$$

where the constant 76 cm Hg/atm is applied to obtain the solubility at a standard pressure of 1 atmosphere.

B. TYPICAL CALCULATION

A calculation is made of a typical example using the data obtained for hydrogen with ethylene propylene (Parker Seal No. 529) at a temperature of 202°F. For example, the permeation rate dV/dt was obtained from the slope of the curve of the volume of the permeating gas vs time (see Figure 4). The permeation rate in this case was

$$dV/dt = 1.23 \times 10^{-4} \text{ std cm}^3/\text{sec} \quad . \qquad \ldots(4)$$

The silicone elastomer thickness (d) was 0.171 cm and the cross-sectional area (A) exposed to the diffusant gas was 29.4 cm^2. The partial pressure or driving force ΔP of the diffusant gas, hydrogen, was 10.0 cm of Hg. The permeability, $\overline{P}$, calculated from the relationship given in Equation (1) is as follows:

$$\overline{P} = \frac{1.23 \times 10^{-4} \text{ cm}^3/\text{sec} \times 0.171 \text{ cm}}{29.4 \text{ cm}^2 \times 10.0 \text{ cm Hg } (\Delta P)}$$

$$= 7.15 \times 10^{-8} \text{ Std cm}^3 \text{ gas-cm/sec/cm}^2\text{/cm Hg } (\Delta P) \quad . \quad \ldots(5)$$

The diffusion coefficient, D, was calculated from the lag time L, in this case 540 sec, and the thickness of the membrane by use of Equation (2)

$$D = \frac{(0.171 \text{ cm})^2}{6 \times 540 \text{ sec}} = 9.03 \times 10^{-6} \text{ cm}^2/\text{sec} \quad . \qquad \ldots(6)$$

The solubility was obtained from Equation (3) using the values of $\overline{P}$ and D obtained in (5) and (6), respectively.

$$\sigma = \frac{7.15 \times 10^{-8} \text{ std cm}^3 \text{ gas-cm/sec/cm}^2\text{/cm Hg} \times 76.0 \text{ cm Hg}}{9.03 \times 10^{-6} \text{ cm}^2/\text{sec}}$$

$$\sigma = 0.60 \text{ std cm}^3 \text{ gas/cm}^3 \text{ elastomer} \quad .$$

C. DATA PRECISION

The precision of the data presented for the permeability ($\overline{P}$), the diffusion coefficient (D) and the solubility (σ) are examined with respect to the measurements taken.

1. Permeability

The permeability of the gas through the elastomer is calculated in the "time-lag" technique by use of Equation (1). This entails determination of the permeation rate, dV/dt, from the slope of the mass or volume flow of the differing gaseous species through the elastomer membrane of thickness d and having a cross sectional area A under a pressure gradient ΔP. The volume of the diffusing gas (at standard temperature and pressure) was determined from its concentration and volume in the low pressure chamber, i.e., V = (c) x (v). The concentration (c) was determined to a precision of ±15%; the chamber volume (v) to ±0.25%.

The thickness of the elastomer membrane was measured to within ±0.001 inch. In general, the membranes used in these tests were 0.080 in. thick, i.e., thus the thickness was determined to a precision of ~1%. However, the greatest source of uncertainty in d is due to nonuniformity of the thickness of the test specimen. Some test specimens varied as much as ±10% in thickness. The thickness used in these calculations was determined from an arithmetical average of several measurements taken over the surface of the specimen. Error in the measurement of the area of the membrane is a small factor, i.e., ±0.001 in. in a diameter of 2.5 in. and can be neglected. However, the effective area of the membrane is greater than the area directly exposed to the gas due to permeation through the elastomer under the edges of the clamp. For thin specimens used here this factor is small, i.e., of the order of ±2%. Lastly, the pressure gradient ΔP was determined to at least ±1% or better. Thus the probable error in $\overline{P}$ at a given temperature is of the order of ±18%. However, the temperature uncertainty

if of the order of ±3°F. The permeation rate in a typical case varies approximately 1% per degree F. Thus the data reported for $\overline{P}$ have a probable error of approximately ±20%.

The permeability data were treated with a computerized "least square" calculational method to obtain the best fit of log $\overline{P}$ as a function of 1K(°K) in the form $\overline{P} = AC^{B/T°K}$ where A and B are constants. Refined plots of log permeability vs 1/T(°K) for each of the elastomers were made. Each experimentally determined value of $\overline{P}$ was also compared with the value calculated from the least squares equation.

2. Diffusion Coefficient

The diffusion coefficient, calculated from Equation (2), is a function of the thickness squared divided by the lag time L. However, as stated above, the thickness may vary as much as ±10% in a given membrane. This would result in probable error of ±14% in the d^2 term. Assessment of the probable error in L is difficult because of the very large variation in L for the different gases and the rather large variation with temperature. For gases which have a high permeation rate, such as hydrogen, particularly at high temperature, the probable error in L can be very large.

3. Solubility

In this technique the solubility is determined from the quotient of the permeability $\overline{P}$ and the diffusion coefficient D (Equation 3). Therefore, the probable error in σ would be expected to exceed the probable error in $\overline{P}$ and D.

The geometry of the samples has been selected in these tests primarily to yield optimum values for the permeability $\overline{P}$, i.e., relatively thin large specimens. As a consequence, the precision limits of the solubility data in some cases, particularly for hydrogen and argon, approach the temperature coefficient of solubility over the measured temperature

range. This can result in a large scatter in the values calculated for σ. Care should be exercised in drawing curves through the solubility data presented. It is preferable to consider that the solubility of the gas lies within the range of values reported.

D. TEST SPECIMENS EXAMINED

Tests were made of the permeation rate and solubility of elastomers of potential interest for application in the FFTF/CRBRP Program. These include samples of Buna N, Buna S, butyl rubber, ethylene-propylene, polyacrylics, silicones and polyurethanes. Samples of elastomers from different vendors were examined for comparison of their permeability and solubility. In some cases different formulations from a manufacturer were also compared.

E. TEST RESULTS

1. Buna N

Four samples of this elastomer were examined for permeability, diffusion coefficient and solubility over the temperature range 100 to 250°F. Samples manufactured by Greene Tweed Company (969) samples of two different lots made by the Minnesota Rubber Company (3664, Samples No. 1 & 2) and a sample made by the Parker Seal Company (N741) were tested. Plots of log $\overline{P}$ vs 1/T°K for these elastomers are given in Figures 5, 6, 7, and 8, respectively. In each case data for the permeability of the gases H_2, Ar, Kr and Xe are given as determined at each of the experimental test temperatures $\overline{P}_T$. The curves representing the permeability for each of the gases were drawn from the equation ($\overline{P} = A + e^{-B/T(°K)}$ where A and B are constants) determined from least squares fit of the experimentally determined points. A measure of fit of each of the experimental data points ($\overline{P}_T$) is made by comparing the permeability (P_{LS}) calculated from the least squares equation (at the same temperature). The values for $\overline{P}_T$, $\overline{P}_{LS}$ and for the constants A and B are given for each of the elastomers in Figures 5, 6, 7 and 8.

Data for the solubility range and for the diffusion coefficient for H_2, Ar, Kr and Xe at the experimental test temperatures are given respectively in Tables 1 and 2.

2. Buna S

Two samples of the elastomer Buna S were examined over the temperature range 100 to 250°F. These were samples manufactured by the Minnesota Rubber Company (480DR) and by Parker Seal Company (G244).

Plots for log $\overline{P}$ vs 1/T(°K) are given in Figures 9 and 10 respectively. The permeability $\overline{P}$ obtained from the tests at three temperatures 101, 183 and 251°F are also given. Corresponding values of the permeability calculated from the least squares equation (the constants A and B are given in Figures 9 and 10) are also given.

Solubility data for H_2, Ar, Kr and Xe are given in Table 1. Values for the diffusion coefficient (D) are given in Table 3.

3. Butyl Rubber

One sample of butyl rubber manufactured by the Parker Seal Company (B318-70) was tested. Permeability data for H_2, Ar, Kr and Xe are shown in Figure 11. Constants for the least squares equations and for calculated values of P_{LS} are also given. Data for the solubility range are given in Table 1; for the diffusion coefficient in Table 4.

4. Ethylene-Propylene

Four samples of ethylene-propylene elastomer materials were examined over the temperature range 100 to 300°F. These included samples made by Greene Tweed Company (952), Minnesota Rubber Company (559N) and two sample by the Parker Seal Company (E529) and E692).

Plots of log $\overline{P}$ vs 1/T(°K) for these four gases in these elastomers are given in Figures 12, 13, 14 and 15. Values for the constants in the least squares equation are given. The experimental determined values of P_T and calculated values P_{LS} are also reported.

Data for the solubility of H_2, Ar, Kr and Xe and for the diffusion coefficient of these gases are given in Tables 1 and 5 respectively.

5. Polyacrylic

Samples of polyacrylic made by the Minnesota Rubber Company (335GA) and the Parker Seal Company (A607) were tested over the temperature range 100 to 300°F. Data for log $\overline{P}$ vs 1/T for the Minnesota Rubber and Parker Seal polyacrylics are given in Figures 16 and 17. Values for the constants in the least squares equation of the data are also given.

The solubility of these gases in these polyacrylic elastomers is given in Table 1; the diffusion coefficient in Table 6.

6. Silicone

Silicone rubber specimens made by the Greene Tweed Company (407), Minnesota Rubber Company (71417) and the Parker Seal Company (S684) were tested over the temperature range 100 to 300°F.

Data for the permeability ($\overline{P}$) as a function of reciprocal temperature (1/T°K) are given in Figures 18, 19 and 20.

The solubility and diffusion coefficient of H_2, Ar, Kr and Xe in these silicone elastomers are shown in Tables 1 and 7 respectively.

7. Urethane

The polyurethane elastomers made by Greene Tweed Company (379), Minnesota Rubber Company (FX522) and two by Parker Seal Company (P642 and P648) were examined over the temperature range 100 to 200°F.

Data for the permeability of H_2, Ar, Kr and Xe in these elastomers are given in Figures 21, 22, 23 and 24. Solubility of these gases are shown in Table 1; the diffusion coefficient is given in Table 8.

IV. SUMMARY OF RESULTS

The permeability, diffusion coefficient, and solubility of hydrogen argon, krypton and xenon, were determined over the temperature interval 100 to 300°F in several different elastomer materials of interest to the FFTF/CRBRP Cover Seal Program. These materials include Buna N (nitrile), Buna S, butyl, ethylene-propylene, silicone, and urethane rubbers. The permeability ($\bar{P}$) for each of these gases in the elastomer is compared at a temperature of 150°F,* in Table 9. As a group the silicone elastomer shows the highest permeability to these gases; Buna N and urethane the lowest. In all cases, excepting the silicone elastomes, the permeability of H_2 was greater than the noble gases at 150°C. In the silicone elastomers the permeability of the noble gases in some cases (particularly Xe) exceeds the permeability of H_2. Surprisingly, in all cases, except two, the permeability of Xe exceeds the permeability of Ar (e.g., silicone, Greene Tweed, 407 and urethane, Parker Seal, P642). In the majority of cases $\bar{P}_{Xe} > P_{Kr}$ at this temperature. This suggests that specific interactions occur between the elastomer and the noble gas penetrants, the interaction being greater with the larger, more polarizable xenon.

The permeability data obtained for hydrogen is compared with data in the literature[4] for the elastomers Buna S, butyl and silicone rubbers at ambient-temperature (Table 10). In each case it can be seen that the values for $\bar{P}$ obtained in this work are similar to the value reported in the literature.[4] The permeabilities for the different manufacturers for the Buna S and silicone elastomer bracket the literature value.

---

*For comparison at other temperature see the individual figures of the Arrhenius plots of log $\bar{P}$ vs 1/T(°K)

The diffusion coefficient (D) was highest for the silicone elastomers lowest for the urethane samples. The diffusion coefficient in general, was approximately the same in H_2 and in the noble gases.

The solubility of H_2, Ar, Kr and Xe was highest in the silicone elastomers lowest in the Buna N rubbers except Xe which had its lowest solubility in butyl rubber.

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TABLE 1

SOLUBILITY OF GASES IN ELASTOMERIC MATERIALS

Elastomer	Vendor	Temperature Range (°F)	Solubility Range (cm^3 gas/cm^3 elastomer)			
			Gas			
			H_2	Ar	Kr	Xe
Buna N (969)	Greene Tweed	100-250	0.14-0.32	0.01-0.03	0.09-0.12	0.20-0.27
Buna N (366Y) No. 1	Minnesota Rubber	100-250	0.09-0.24	0.02-0.09	0.11-0.17	0.25-0.46
Buna N (366Y) No. 2	Minnesota Rubber	100-250	0.04-0.42	0.04-0.11	0.18-0.22	0.29-0.33
Buna N (N741)	Parker Seal	100-250	0.08-0.26	0.01-0.07	0.05-0.24	0.14-0.36
Buna S (480DR)	Minnesota Rubber	100-250	0.30-1.09	0.07-0.11	0.32-0.49	0.41-0.65
Buna S (G244)	Parker Seal	100-250	0.10-0.46	0.02-0.16	0.08-0.23	0.04-0.31
Butyl (B318-70)	Parker Seal	100-250	0.29-0.69	0.08-0.12	0.14-0.23	0.11-0.21
EPR (952)	Greene Tweed	100-300	0.10-0.39	0.07-0.10	0.22-0.27	0.22-0.38
EPR(559N)	Minnesota Rubber	100-300	0.16-0.39	0.05-0.10	0.12-0.20	0.28-0.54
EPR (E529)	Parker Seal	100-300	0.60-0.85	0.11-0.19	0.07-0.43	0.27-0.64
EPR(E692)	Parker Seal	100-300	0.31-0.44	0.11-0.14	0.12-0.24	0.38-0.91
Polyacrylic (335GA)	Minnesota Rubber	100-300	0.19-1.41	0.09-0.21	0.20-0.64	0.31-1.14
Polyacrylic (A607)	Parker Seal	100-300	0.80-1.53	0.08-0.21	0.36-0.69	0.53-0.93
Silicone (407)	Green Tweed	100-300	0.46-0.71	0.28-0.82	0.29-0.88	0.16-1.10
Silicone (71417)	Minnesota Rubber	100-300	0.70-1.62	0.38-0.52	0.86-1.74	0.33-1.21
Silicone (S684)	Parker Seal	100-300	1.05-3.29	0.29-0.91	0.95-1.94	1.55-3.53
Urethane (379)	Greene Tweed	100-200	0.27-0.37	0.07-0.08	0.14-0.24	0.24-0.50
Urethane (FX522)	Minnesota Rubber	100-200	0.47-1.11	0.06-0.10	0.16-0.40	0.24-0.56
Urethane (P642)	Parker Seal	100-200	0.40-0.45	0.07-0.15	0.08-0.35	0.14-0.52
Urethane (P648)	Parker Seal	100-200	0.03-0.25	0.04-0.31	0.22-0.58	0.33-0.51

TABLE 2. DIFFUSION COEFFICIENT (D) OF H_2, Ar, Kr and Xe IN BUNA N ELASTOMERS

Greene Tweed (969)		Minnesota Rubber (366Y, No. 1)		Minnesota Rubber (366Y, No. 2)		Parker Seal (N741)	
Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)
			Hydrogen				
101	7.18-7*	101	6.60-7	101	6.40-7	101	5.70-7
178	3.06-6	179	6.24-6	171	3.10-6	178	2.42-6
250	6.16-6	251	1.42-5	244	7.87-1	251	1.17-5
			Argon				
101	1.55-6	101	4.21-7	101	3.72-7	101	1.01-6
178	2.54-6	179	5.70-6	171	2.01-6	178	5.73-6
250	5.60-6	251	1.18-5	244	5.43-6	251	1.26-5
			Krypton				
101	9.11-8	101	2.37-7	101	2.44-7	101	6.07-8
178	8.95-7	179	1.74-6	171	1.46-6	178	1.16-6
250	4.20-6	251	5.33-6	244	3.83-6	251	5.42-6
			Xenon				
101	4.77-8	101	1.21-7	101	1.52-7	101	4.30-8
178	5.15-7	179	7.37-7	171	1.00-6	178	7.80-7
250	2.19-6	251	3.37-6	244	3.07-6	251	2.83-6

*-7 = $\times 10^{-7}$, etc.

FORM 716-1 (REV. 3-73)

TABLE 3. DIFFUSION COEFFICIENT (D) OF H_2, Ar, Kr and Xe IN BUNA S ELASTOMERS

Minnesota Rubber (480 DR)		Parker Seal (G 244)	
Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)
	Hydrogen		
101	7.76-7*	101	4.69-6
180	4.44-6	183	5.47-6
253	1.42-5	251	1.16-5
	Argon		
101	1.48-6	101	2.33-6
253	9.48-6	183	5.47-6
		251	8.72-6
	Krypton		
101	6.26-7	101	9.21-7
180	2.56-6	183	3.93-6
253	6.46-6	251	6.20-6
	Xenon		
101	4.96-7	101	3.69-7
180	1.92-6	183	2.66-6
253	4.40-6	251	5.58-6

* -7 = $\times 10^{-7}$, etc.

TABLE 4. DIFFUSION COEFFICIENTS (D) OF H_2, Ar, Kr and Xe IN BUTYL RUBBER

Parker Seal (B-318-70)			
Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)
Hydrogen		Krypton	
95	5.59-7*	95	8.11-8
180	2.16-6	180	7.21-7
255	3.95-6	255	2.43-6
Argon		Xenon	
95	1.44-7	95	5.01-8
180	7.72-7	180	6.28-7
255	3.24-6	255	1.83-6

* -7 = $\times 10^{-7}$, etc.

TABLE 5. DIFFUSION COEFFICIENTS (D) OF H_2, Ar, Kr and Xe IN EPR ELASTOMERS

Greene Tweed (952)		Minnesota Rubber (559N)		Parker Seal (E529)		Parker Seal (E692)	
Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)
			Hydrogen				
101	1.58-6*	101	3.76-6	101	1.35-6	100	1.07-6
202	1.88-5	202	1.13-5	202	5.62-6	201	5.75-6
307	1.42-5	302	1.89-5	309	2.32-5	304	1.94-5
			Argon				
101	1.24-6	101	1.87-6	101	1.37-6	100	1.18-6
202	5.81-6	202	1.17-5	202	5.15-6	201	8.96-6
307	2.36-5	302	5.23-5	309	2.18-5	304	1.94-5
			Krypton				
101	6.31-7	101	1.18-6	101	8.07-7	100	7.77-7
202	4.30-6	202	7.56-6	202	4.12-6	201	7.35-6
307	1.46-5	302	2.72-5	309	2.54-5	304	1.66-5
			Xenon				
101	4.44-7	101	7.09-7	101	6.40-7	100	4.16-7
202	2.93-6	202	5.27-6	202	3.53-6	201	3.80-6
307	1.18-5	302	1.84-5	309	2.25-5	304	1.21-5

* -6 = $\times 10^{-6}$, etc.

TABLE 6. DIFFUSION COEFFICIENTS (D) OF H_2, Ar, Kr and Xe IN POLYACRYLIC ELASTOMERS

Minnesota Rubber (335 GA)		Parker Seal (A 607)	
Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)
	Hydrogen		
99	9.61-7*	100	5.13-7
150	4.64-6	195	2.18-6
199	4.85-6	307	6.06-6
301	8.89-6		
	Argon		
99	7.90-7	100	7.05-7
150	2.13-6	195	4.83-6
199	5.61-6	307	1.56-5
301	1.33-5		
	Krypton		
99	3.72-7	100	3.45-7
150	1.57-6	195	2.51-6
199	2.81-6	307	6.77-6
301	8.89-6		
	Xenon		
99	1.78-7	100	2.06-7
150	9.52-7	195	1.57-6
199	2.13-6	307	5.88-6
301	5.08-6		

* -7 = $\times 10^{-7}$, etc.

TABLE 7. DIFFUSION COEFFICIENT (D) OF H_2, Ar, Kr and Xe IN SILICONE ELASTOMERS

Greene Tweed (407)		Minnesota Rubber (71417)		Parker Seal (S684)	
Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)
		Hydrogen			
100	1.32-5*	100	3.98-6	101	8.03-6
204	3.38-5	197	1.00-5	195	4.08-6
303	1.22-4	301	1.10-4	313	1.42-5
		Argon			
100	1.56-5	100	1.10-5	101	1.21-5
204	1.84-5	197	2.06-5	195	1.24-5
303	1.01-4	301	3.88-5	313	2.68-5
		Krypton			
100	8.69-6	100	5.74-6	101	7.42-6
204	1.52-5	197	1.27-5	195	7.41-6
303	4.09-9	301	1.83-5	313	1.79-5
		Xenon			
100	6.68-6	100	6.00-6	101	5.88-6
204	1.29-5	197	1.57-5	195	5.18-6
203	1.52-4	301	6.60-5	313	1.34-5

* -5 = $\times 10^{-5}$, etc.

TABLE 8. DIFFUSION COEFFICIENT (D) OF H_2, Ar, Kr and Xe IN URETHANE ELASTOMERS

Greene Tweed (379)		Minnesota Rubber (FX522)		Parker Seal (P642)		Parker Seal (P648)	
Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)	Temperature (°F)	D (cm^2/sec)
			Hydrogen				
100	4.35-7*	100	2.85-7	103	4.36-7	102	3.25-7
151	1.24-6	152	1.13-6	151	1.75-6	152	8.67-7
201	2.38-6	200	9.95-7	202	3.45-6	201	1.41-5
			Argon				
100	1.87-7	100	2.18-7	103	1.24-7	102	3.17-8
151	9.25-7	152	9.33-7	151	7.61-7	152	1.85-7
201	2.27-6	200	9.95-7	202	1.39-6	201	1.92-6
			Krypton				
100	1.49-7	100	1.12-7	103	1.13-7	102	3.49-8
151	5.56-6	152	7.68-7	151	8.48-7	152	1.83-7
201	1.45-6	200	9.09-7	202	9.21-7	201	6.32-7
			Xenon				
100	7.61-8	100	8.10-8	103	9.47-8	102	3.10-8
151	3.77-7	152	4.10-7	151	6.59-7	152	1.56-7
201	9.41-7	200	7.47-7	202	8.22-7	201	4.84-7

* -7 = $\times 10^{-7}$, etc.

TABLE 9

COMPARISON OF PERMEABILITY ($\bar{P}$) OF H_2, Ar, Kr AND Xe THROUGH ELASTOMERS AT 150°F

Elastomer	Vendor	Permeability ($\bar{P}$) x 10^{-9} at 150°F (Std cm^3 gas-cm/sec-cm^2- cm Hg ΔP)			
		Gas			
		H_2	Ar	Kr	Xe
Buna N (969)	Greene Tweed	4.00	0.47	0.57	0.69
Buna N (366Y) no. 1	Minnesota Rubber	5.00	1.25	1.52	1.80
Buna N (366Y) no. 2	Minnesota Rubber	10.5	1.10	2.11	2.45
Buna N (N741)	Parker Seal	3.52	0.52	0.86	1.02
Buna S (480DR)	Minnesota Rubber	18.0	3.20	8.2	6.90
Buna S (G244)	Parker Seal	17.5	1.25	2.99	5.00
Butyl (B318-70)	Parker Seal	6.30	0.47	0.80	0.65
EPR (952)	Greene Tweed	10.0	3.45	5.55	4.65
EPR(559N)	Minnesota Rubber	16.5	5.75	7.05	12.0
EPR (E529)	Parker Seal	34.5	7.00	11.0	13.5
EPR(E692)	Parker Seal	14.0	5.25	5.60	10.5
Polyacrylic (335GA)	Minnesota Rubber	13.5	2.15	4.50	4.40
Polyacrylic (A607)	Parker Seal	16.0	2.85	5.20	4.85
Silicone (407)	Greene Tweed	155	72	110	66
Silicone (71417)	Minnesota Rubber	105	87	105	140
Silicone (S684)	Parker Seal	195	55	135	195
Urethane (379)	Greene Tweed	4.95	0.74	1.20	1.45
Urethane (FX522)	Minnesota Rubber	5.50	0.56	1.30	1.65
Urethane (P642)	Parker Seal	7.98	1.35	0.97	0.72
Urethane (P648)	Parker Seal	2.24	0.43	0.70	0.78

TABLE 10

PERMEABILITY OF HYDROGEN IN BUNA S, BUTYL, AND SILICONE ELASTOMERS, COMPARED WITH LITERATURE DATA*

Elastomer	Manufacturer	$\overline{P}$ (Std cm^3 gas-cm/sec-cm^2-cm Hg ΔP)
Buna S	Minnesota Rubber, (480DR)	4.8
Buna S	Parker Seal G244	2.8
Buna S	Vendor unknown, Literature*	4.0
Butyl	Parker Seal, B318-70	0.95
Butyl	Appanol B-200, Literature*	0.64
Silicone	Greene Tweed, 407	42
Silicone	Minnesota Rubber, 71417	18
Silicone	Parker Seal, S684	85
Silicone	Vendor unknown, Literature*	66

*See Reference 4

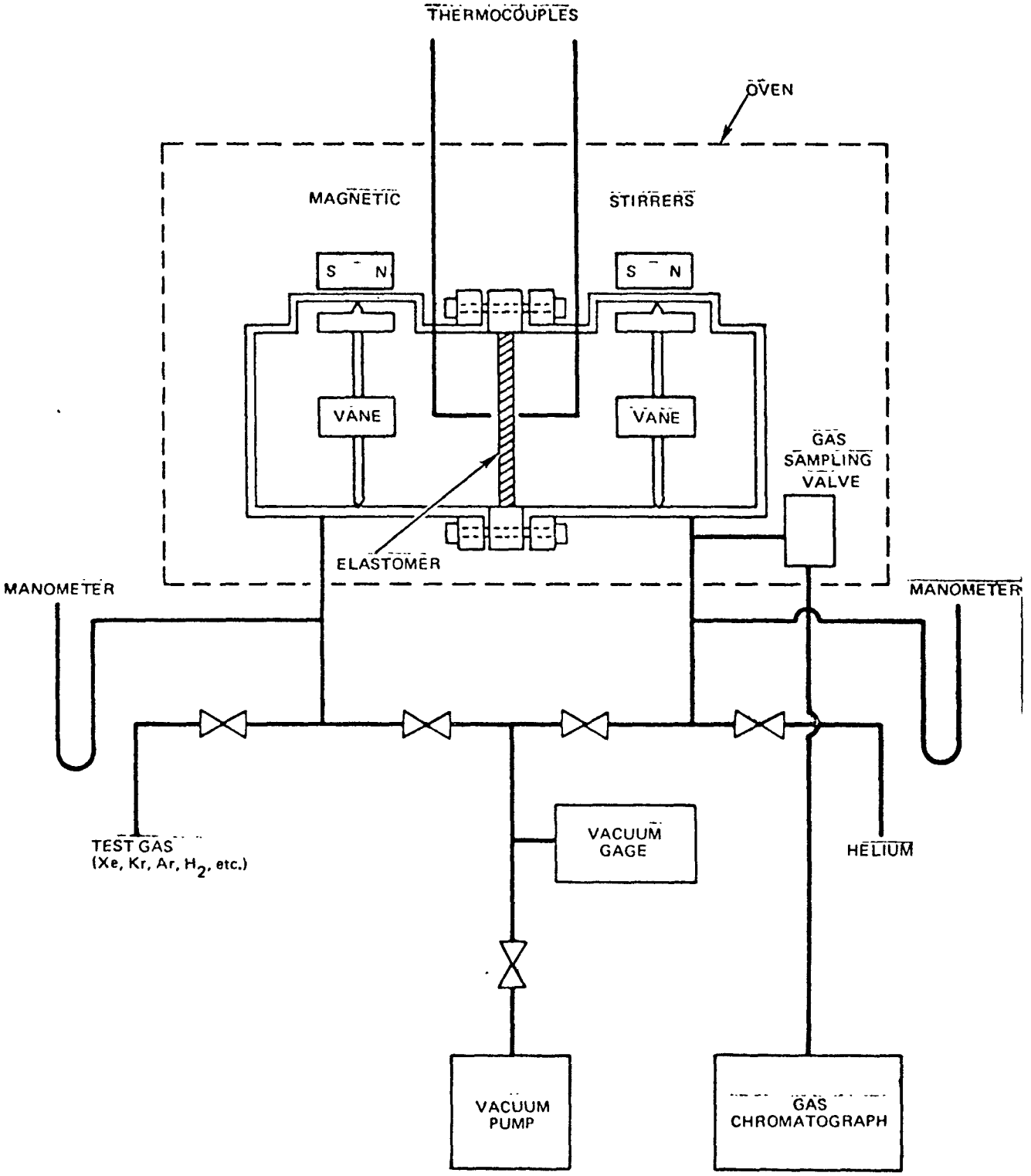


Figure 1. Schematic Diagram of Gas Permeation Apparatus

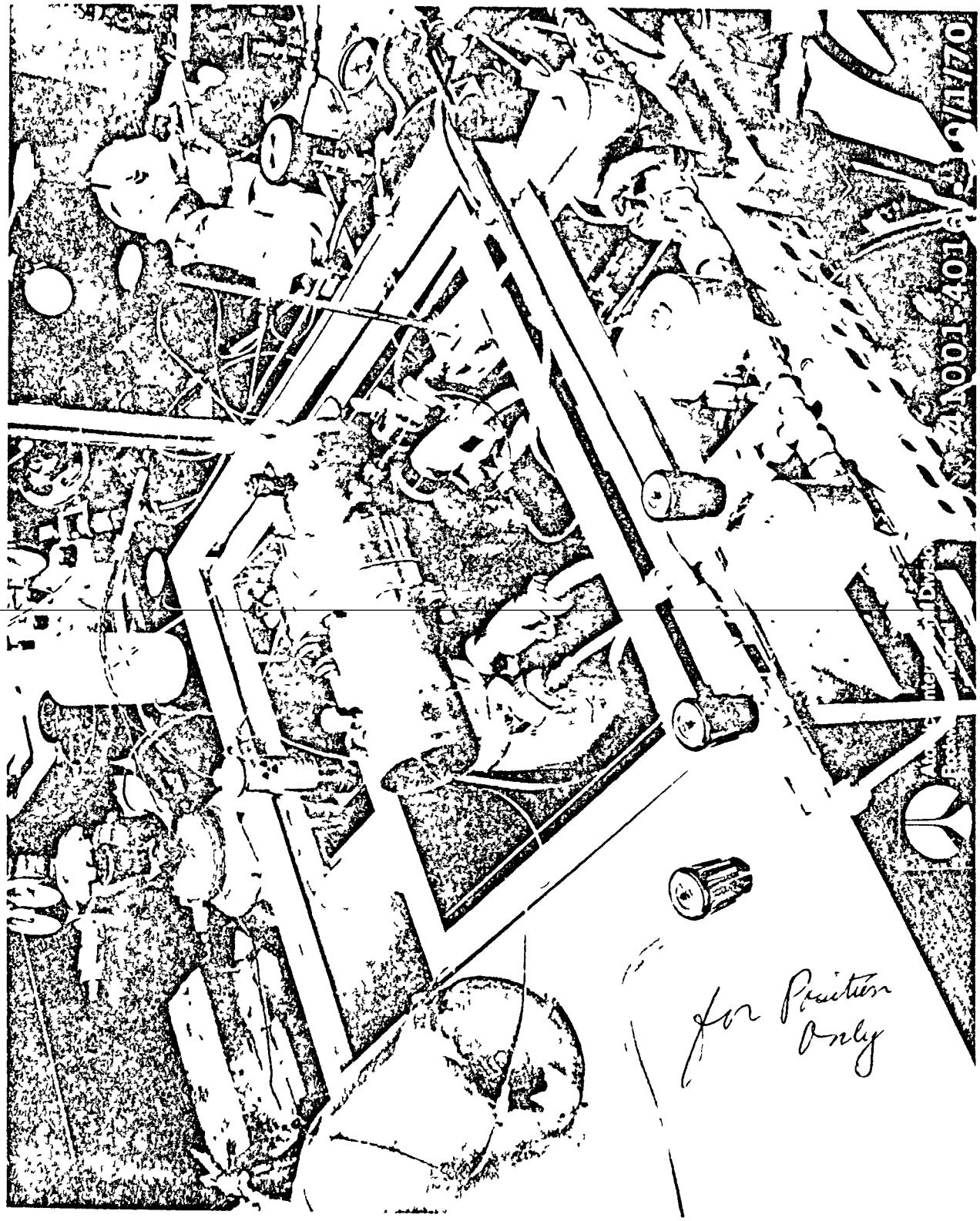


Figure 2. Pictorial View of Gas Permeation Apparatus

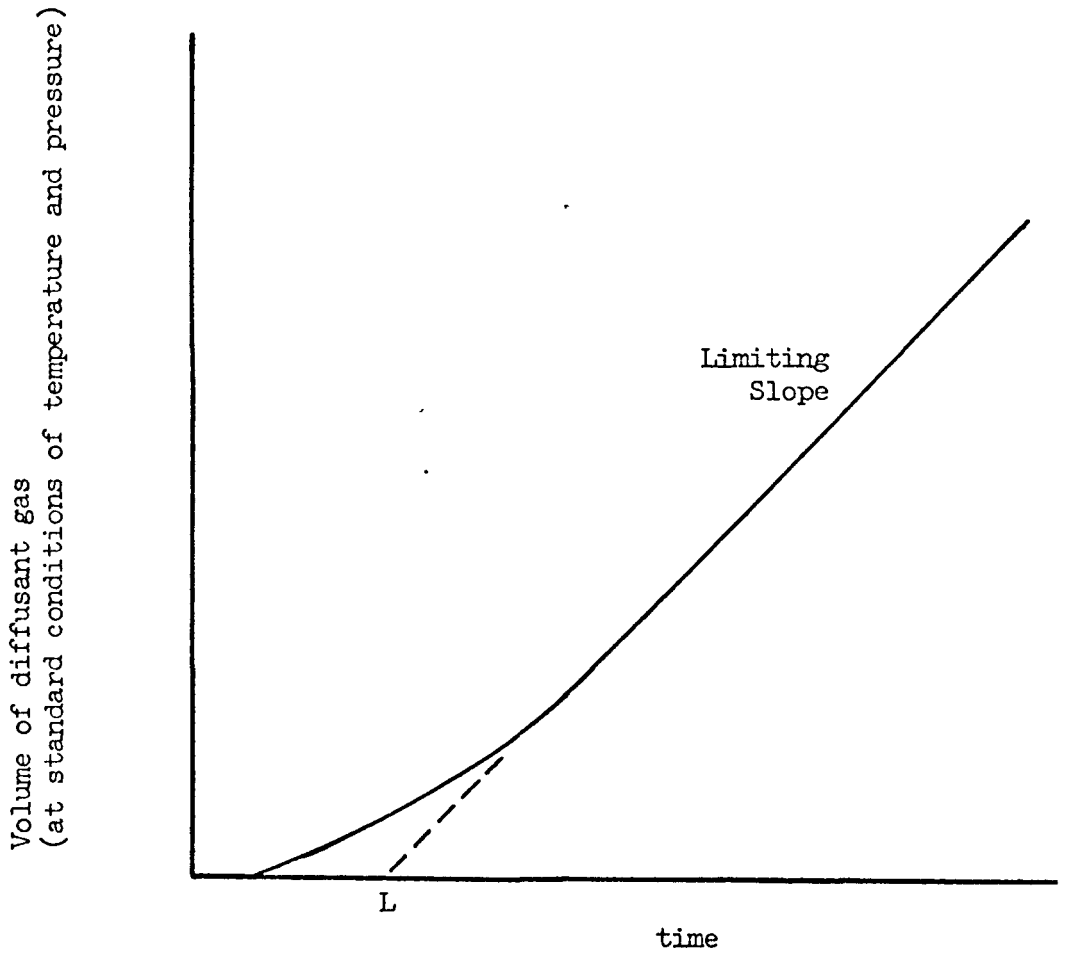


Figure 3. Typical Plot of Volume vs Time for Diffusing Gas at Constant Temperature

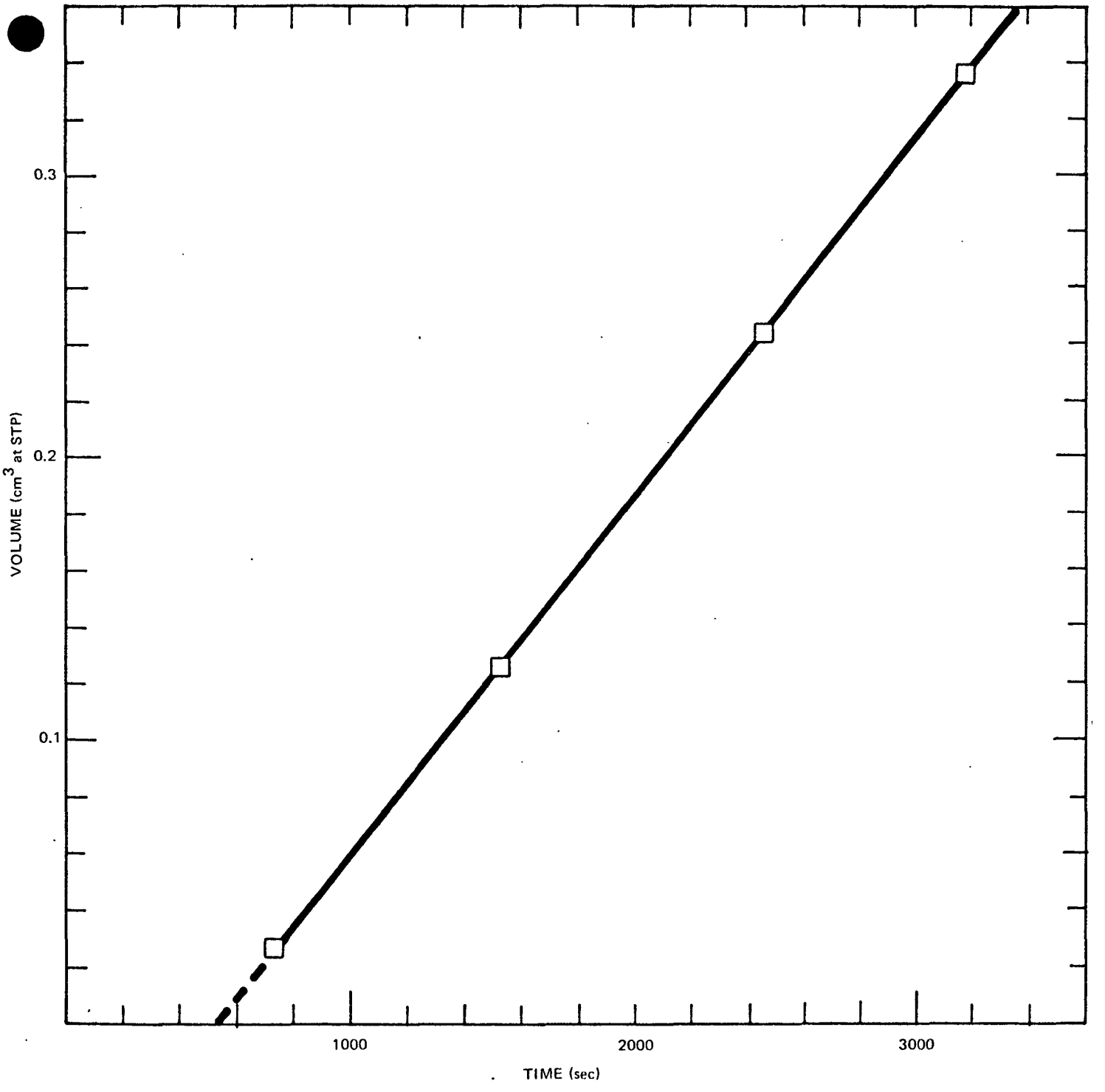


Figure 4. Permeation Rate of Hydrogen Through Ethylene-Propylene Elastomer (Parker Seal No. 529 at 202° F)

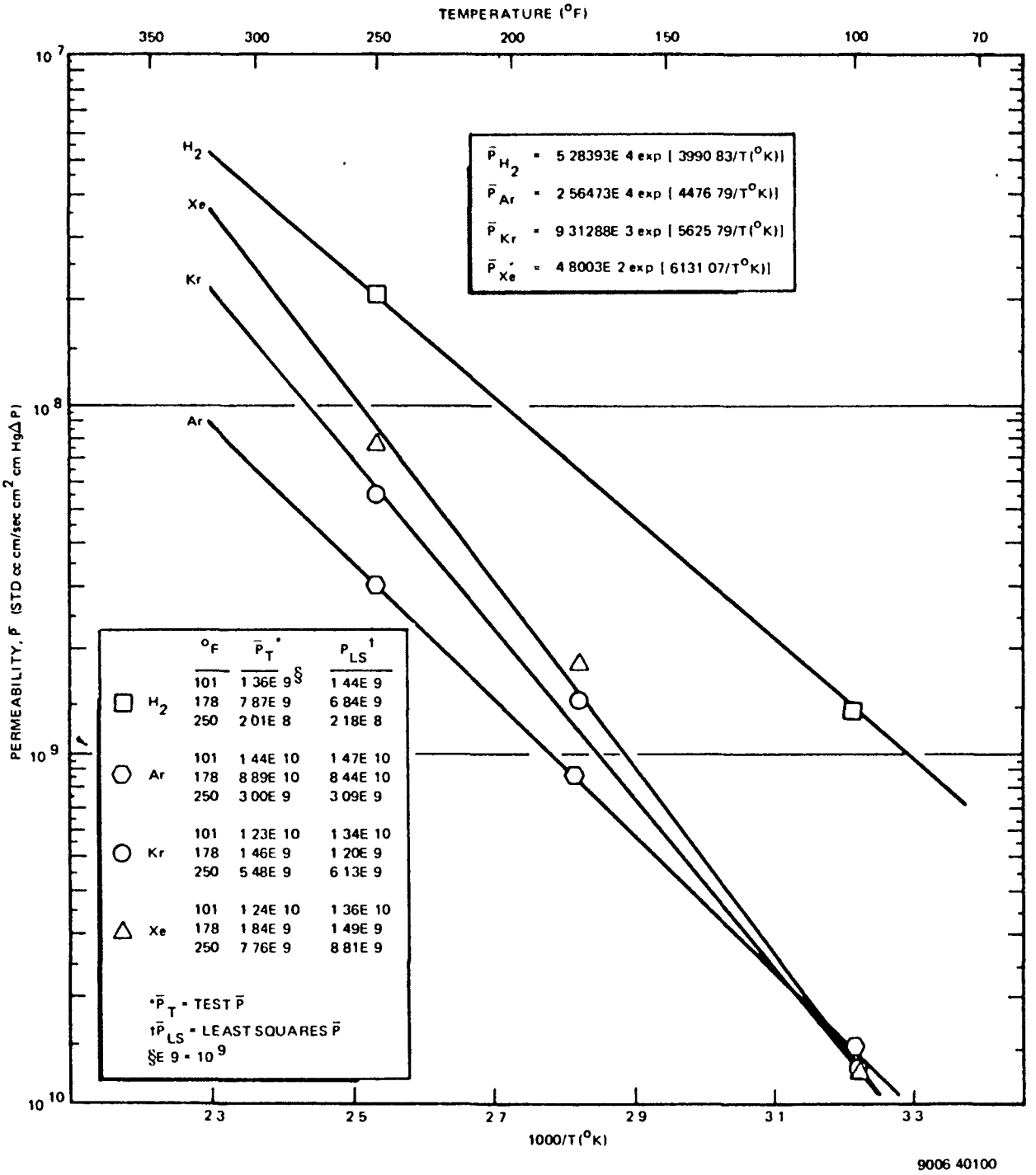


Figure 5. Log $\bar{P}$ vs 1/T(°K) for H_2, Ar, Kr, and Xe for Buna N Rubber, Greene-Tweed Co., Compound 969

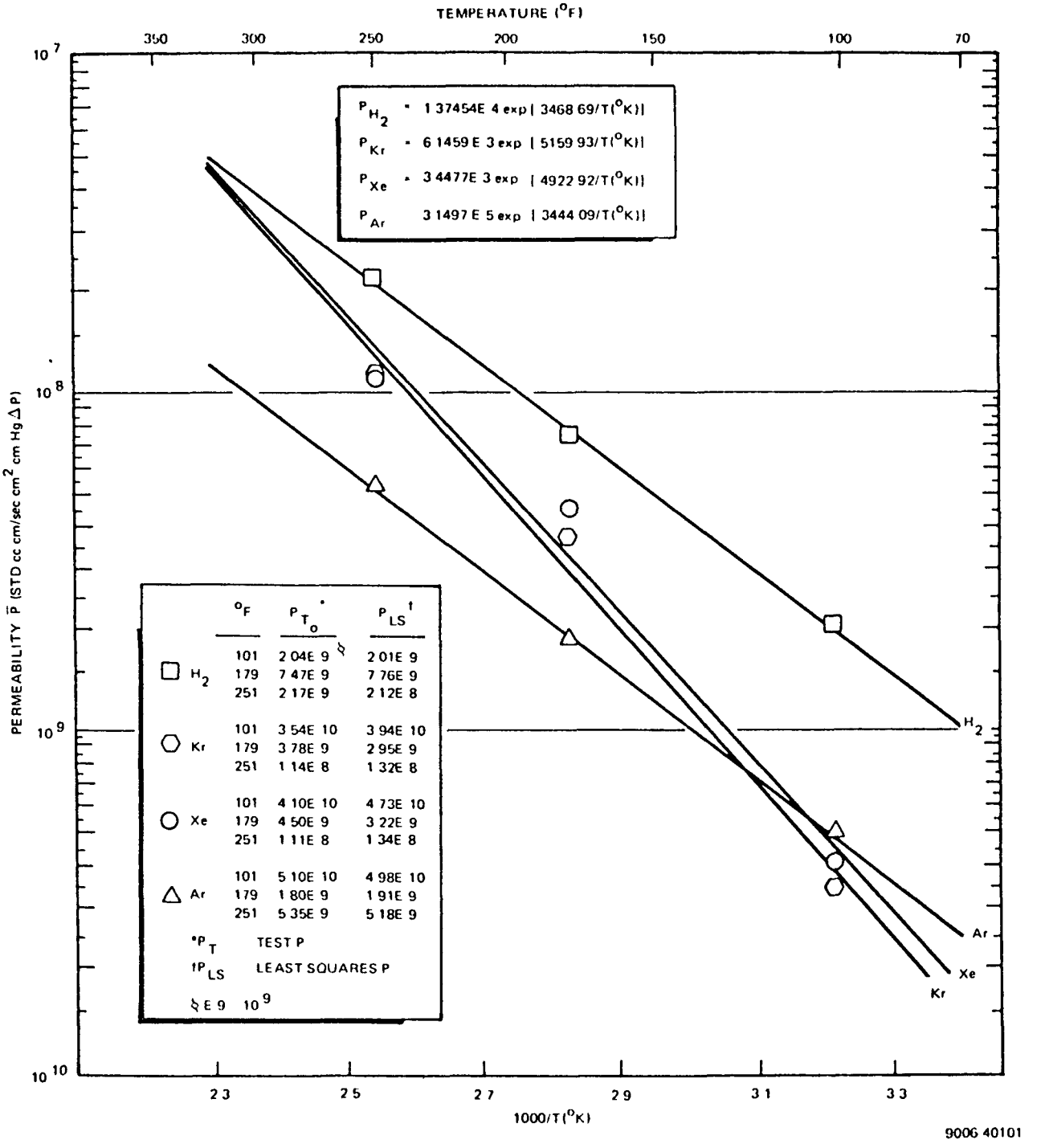
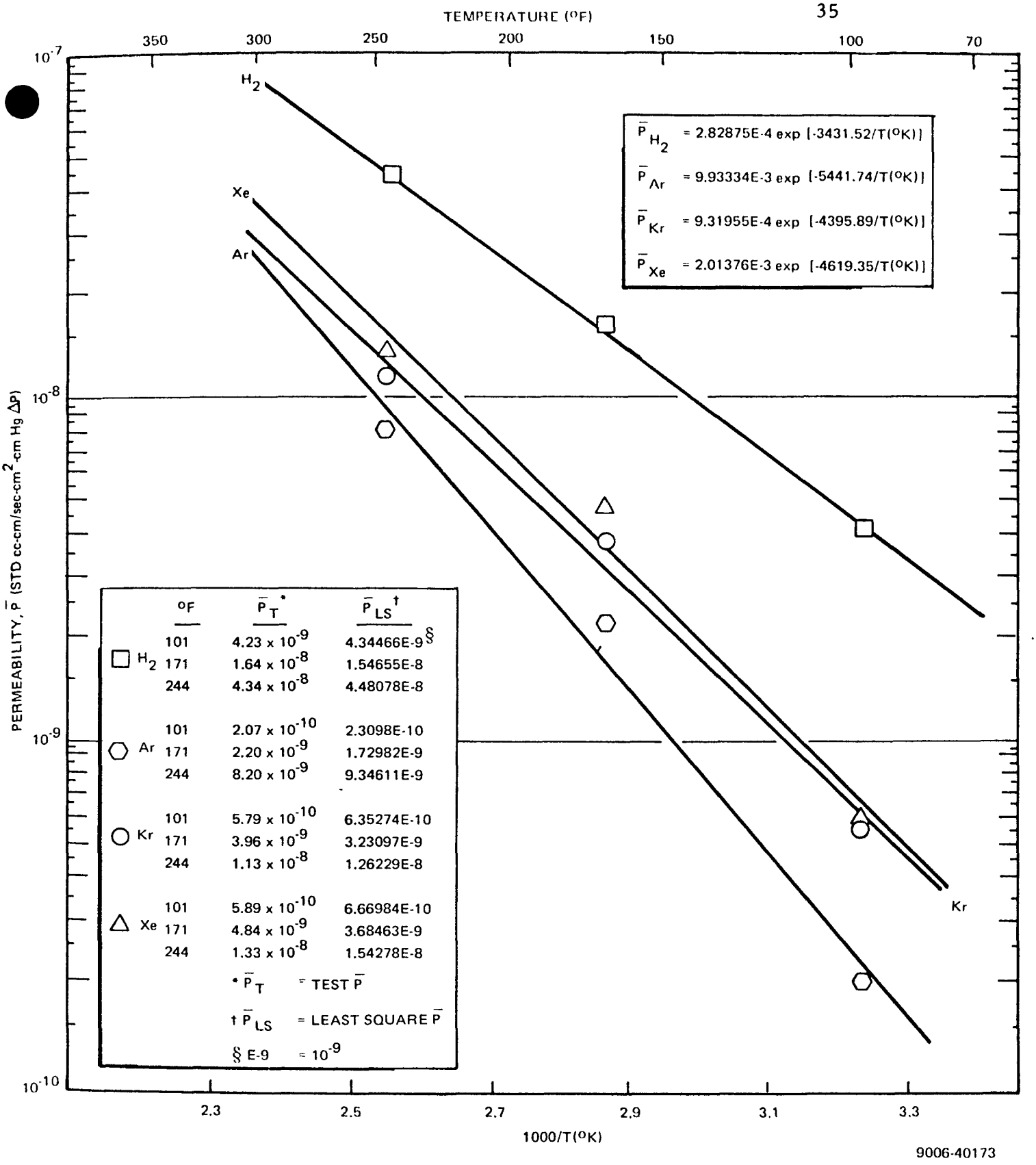


Figure 6. Log $\overline{P}$ vs 1/%(°K) for H_2, Ar, Kr, and Xe for Minnesota Rubber Co., Buna N, Compound 366Y



	°F	$\bar{P}_T$*	$\bar{P}_{LS}$†
□ H_2	101	4.23×10^{-9}	4.34466E-9§
	171	1.64×10^{-8}	1.54655E-8
	244	4.34×10^{-8}	4.48078E-8
⬡ Ar	101	2.07×10^{-10}	2.3098E-10
	171	2.20×10^{-9}	1.72982E-9
	244	8.20×10^{-9}	9.34611E-9
○ Kr	101	5.79×10^{-10}	6.35274E-10
	171	3.96×10^{-9}	3.23097E-9
	244	1.13×10^{-8}	1.26229E-8
△ Xe	101	5.89×10^{-10}	6.66984E-10
	171	4.84×10^{-9}	3.68463E-9
	244	1.33×10^{-8}	1.54278E-8

* $\bar{P}_T$ = TEST $\bar{P}$

† $\bar{P}_{LS}$ = LEAST SQUARE $\bar{P}$

§ E-9 = 10^{-9}

Figure 7. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr, and Xe for Minnesota Buna N (366Y, Batch 982, 2nd Lot)

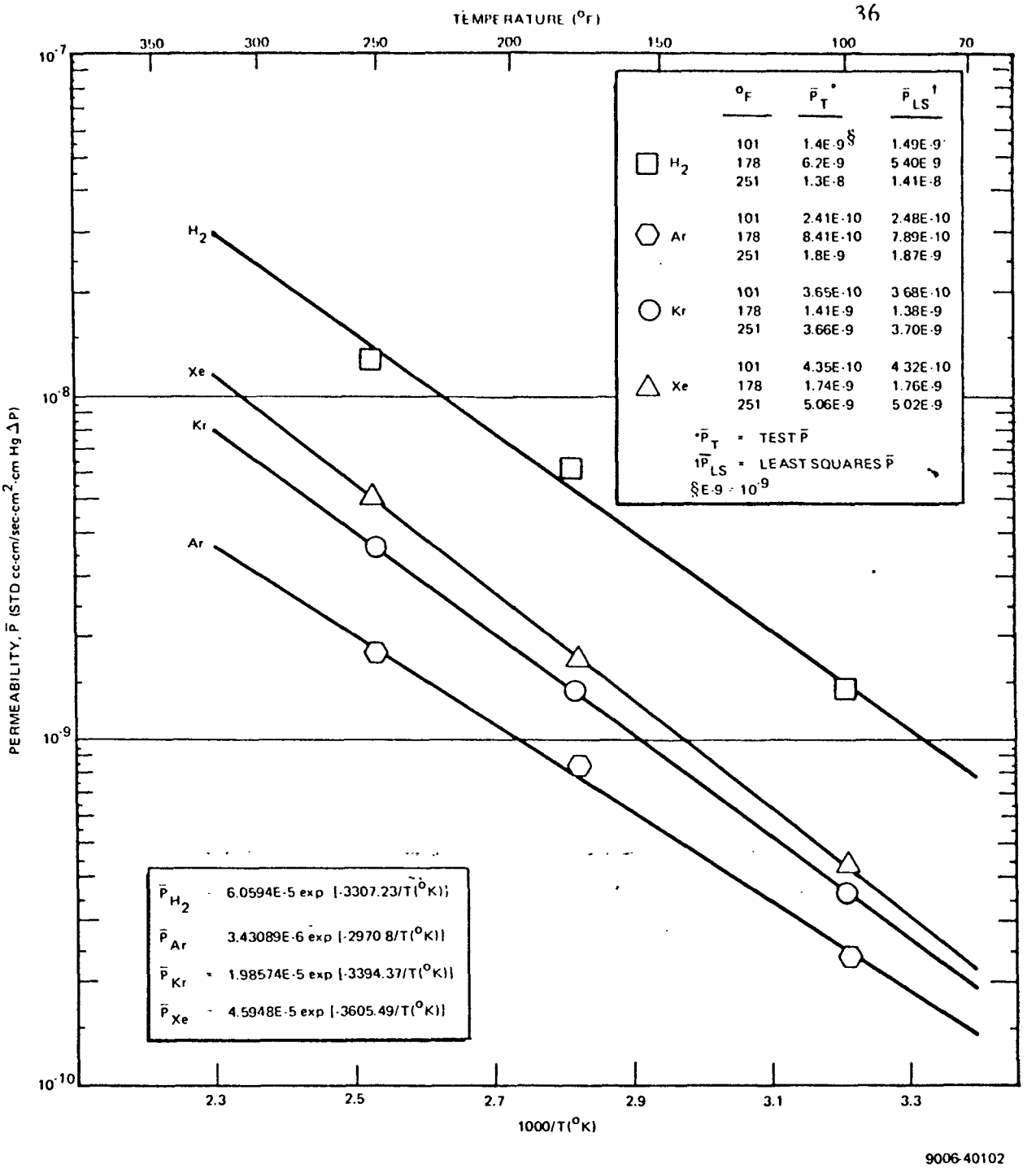


Figure 8. Log $\overline{P}$ vs 1/%(°K) for H_2, Ar, Kr, and Xe for Buna N Rubber, Parker Seal Co., Compound N741

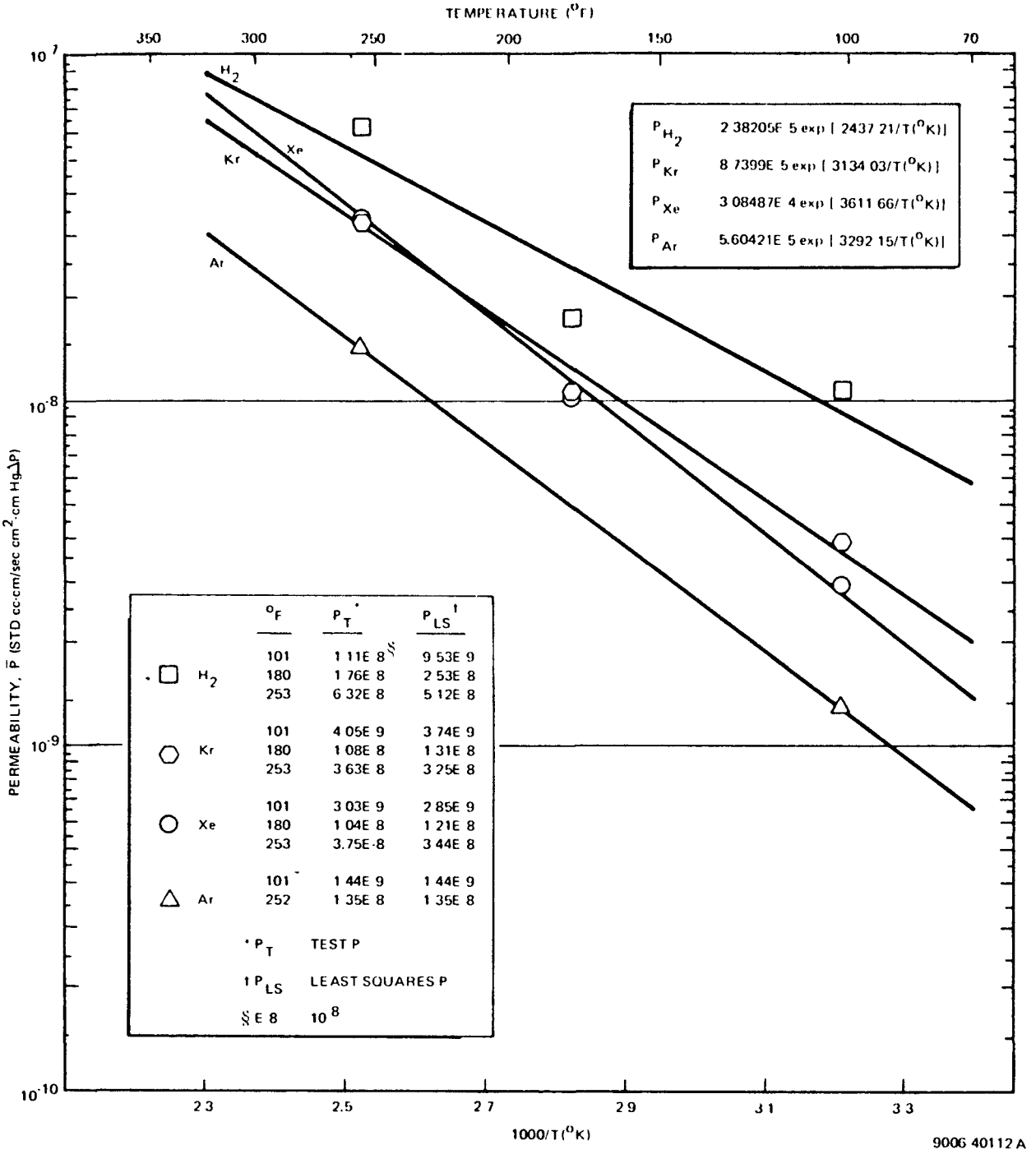


Figure 9. Log $\overline{P}$ vs 1/T(°K) for H_2, Ar, Kr, and Xe for Minnesota Rubber Co., Buna S Compound 480DR

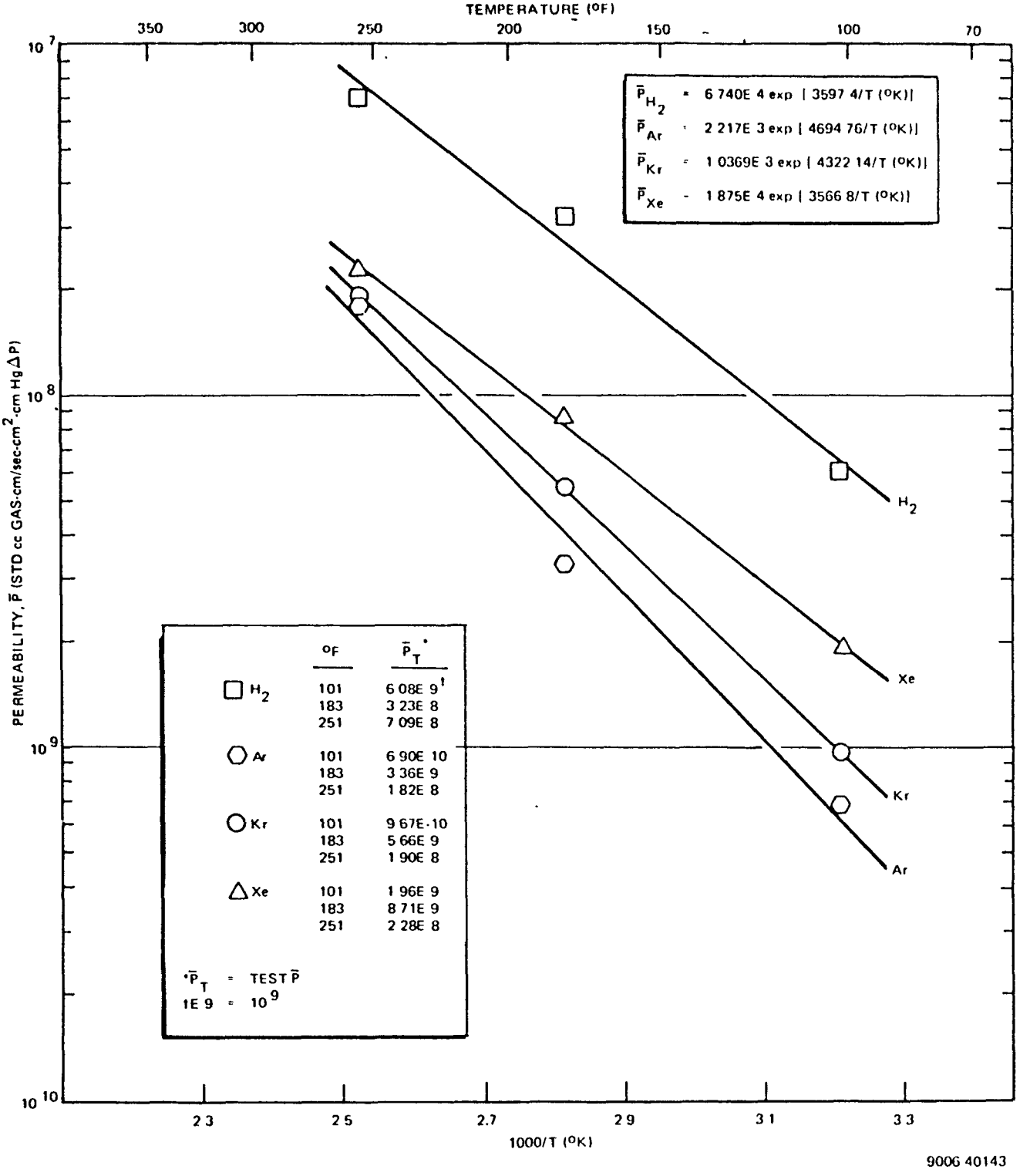
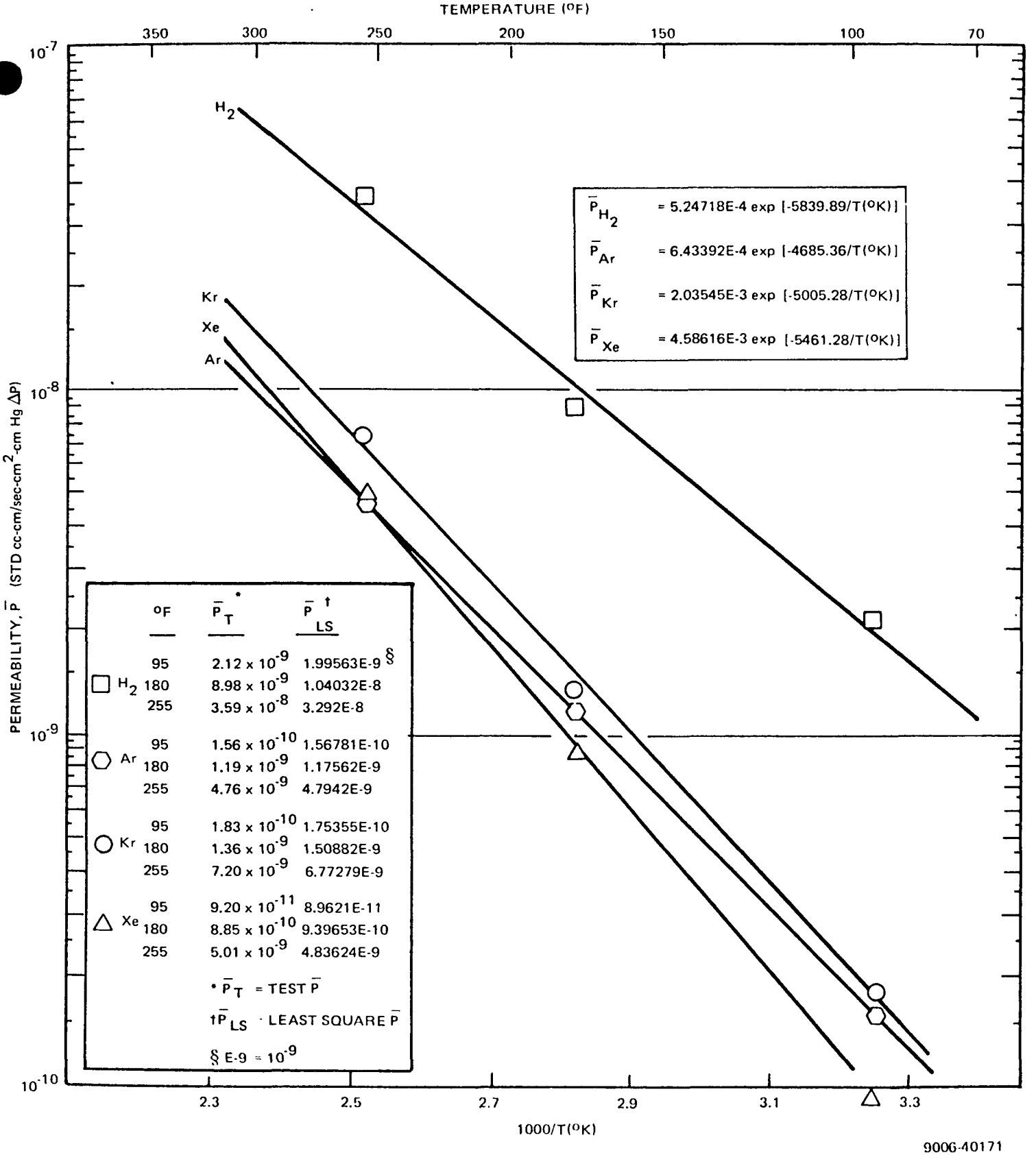


Figure 10. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr, and Xe for Parker Seal Buna S (G244)



	°F	$\bar{P}_T$ *	$\bar{P}_{LS}$ †
□ H_2	95	2.12×10^{-9}	1.99563E-9 §
	180	8.98×10^{-9}	1.04032E-8
	255	3.59×10^{-8}	3.292E-8
⬡ Ar	95	1.56×10^{-10}	1.56781E-10
	180	1.19×10^{-9}	1.17562E-9
	255	4.76×10^{-9}	4.7942E-9
○ Kr	95	1.83×10^{-10}	1.75355E-10
	180	1.36×10^{-9}	1.50882E-9
	255	7.20×10^{-9}	6.77279E-9
△ Xe	95	9.20×10^{-11}	8.9621E-11
	180	8.85×10^{-10}	9.39653E-10
	255	5.01×10^{-9}	4.83624E-9

* $\bar{P}_T$ = TEST $\bar{P}$

† $\bar{P}_{LS}$ · LEAST SQUARE $\bar{P}$

§ E-9 = 10^{-9}

Figure 11. Log $\bar{P}$ vs 1/T (°K) for H_2, Ar, Kr, and Xe for Parker Seal Butyl Rubber (B318-70)

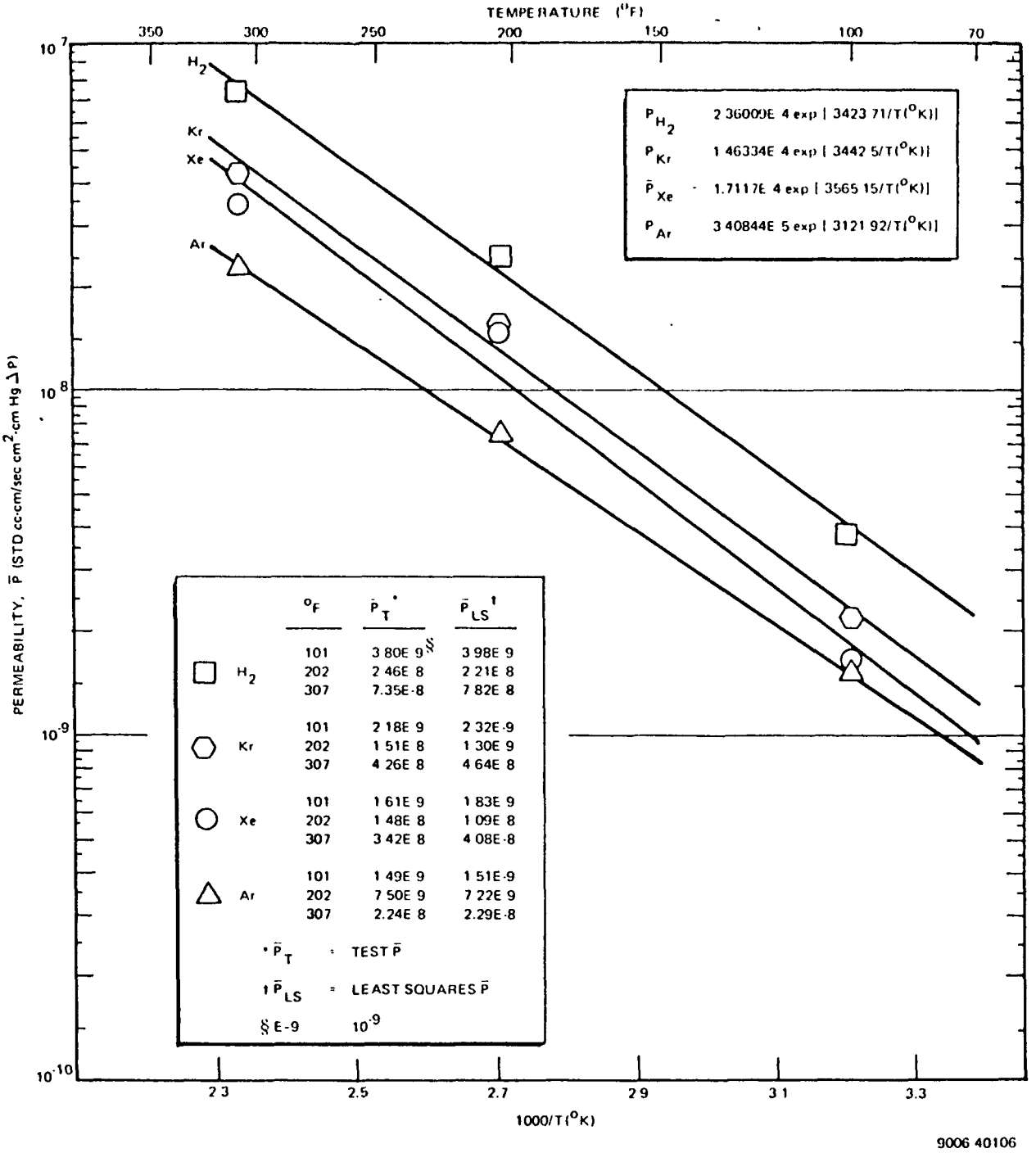
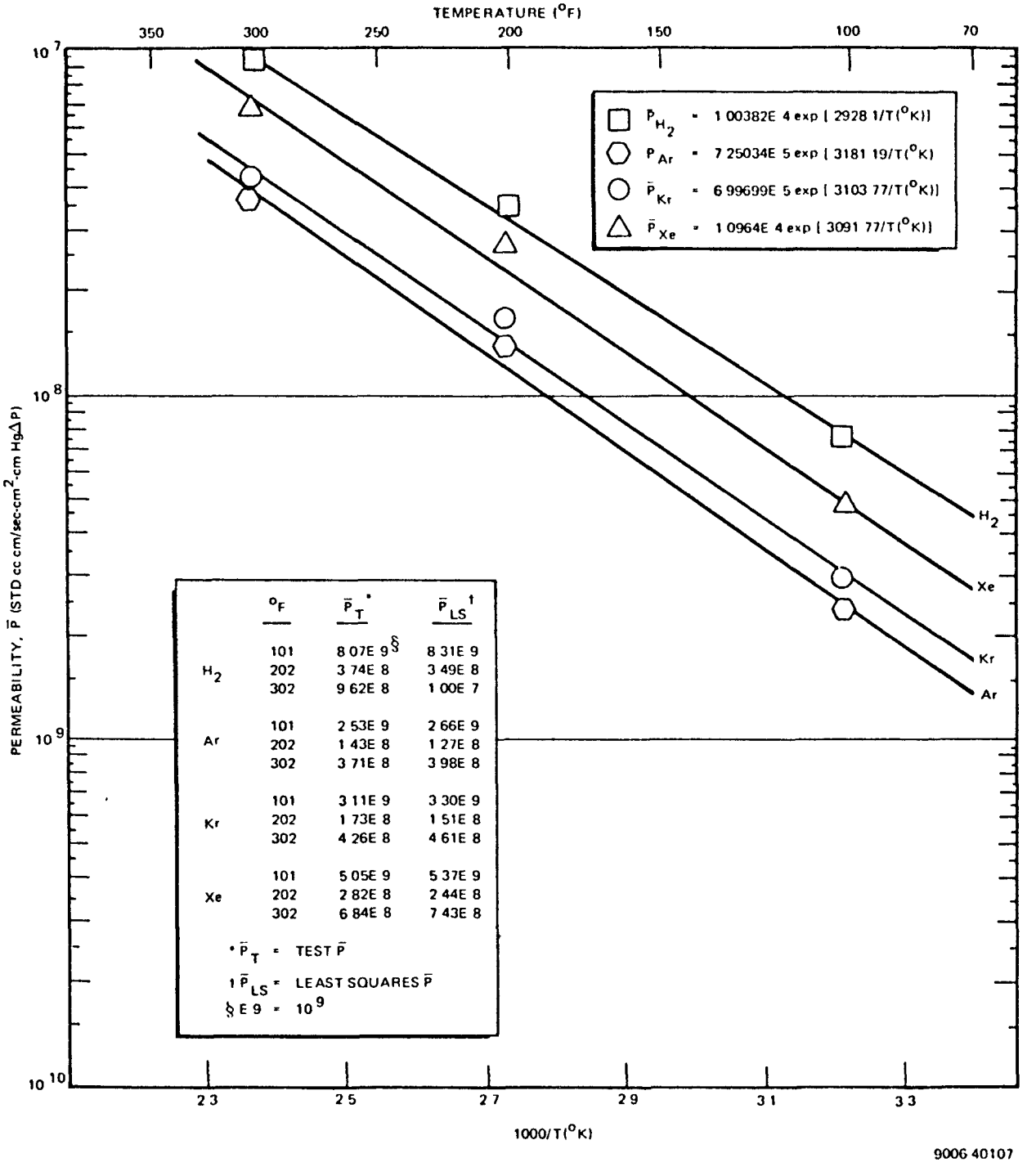


Figure 12. Log $\overline{P}$ vs 1/T(°K) for H_2, Ar, Kr, and Xe for Ethylene-Propylene Rubber, Greene-Tweed Co., Compound 972



	°F	$\bar{P}_T$*	$\bar{P}_{LS}$†
H_2	101	8 07E 9§	8 31E 9
	202	3 74E 8	3 49E 8
	302	9 62E 8	1 00E 7
Ar	101	2 53E 9	2 66E 9
	202	1 43E 8	1 27E 8
	302	3 71E 8	3 98E 8
Kr	101	3 11E 9	3 30E 9
	202	1 73E 8	1 51E 8
	302	4 26E 8	4 61E 8
Xe	101	5 05E 9	5 37E 9
	202	2 82E 8	2 44E 8
	302	6 84E 8	7 43E 8

*$\bar{P}_T$ = TEST $\bar{P}$
†$\bar{P}_{LS}$ = LEAST SQUARES $\bar{P}$
§E 9 = 10^9

Figure 13. Log $\overline{P}$ vs 1/T(°K) for H_2, Ar, Kr, and Xe for Ethylene Propylene Rubber, Minnesota Rubber Co., Compound 559N

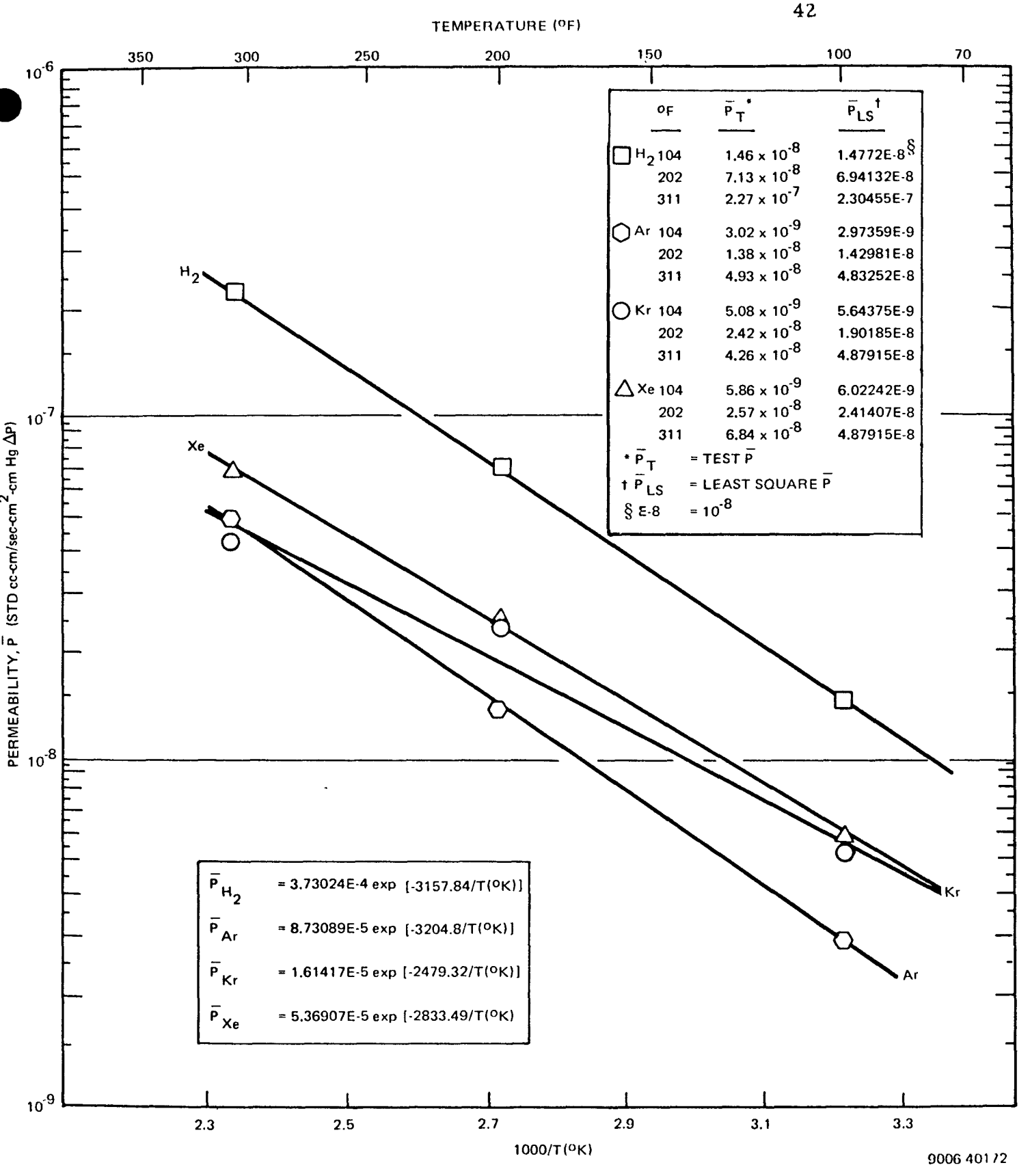


Figure 14. Log $\bar{P}$ vs 1/T (°K) for H_2, Ar, Kr, and Xe for Parker Seal EPR (E529)

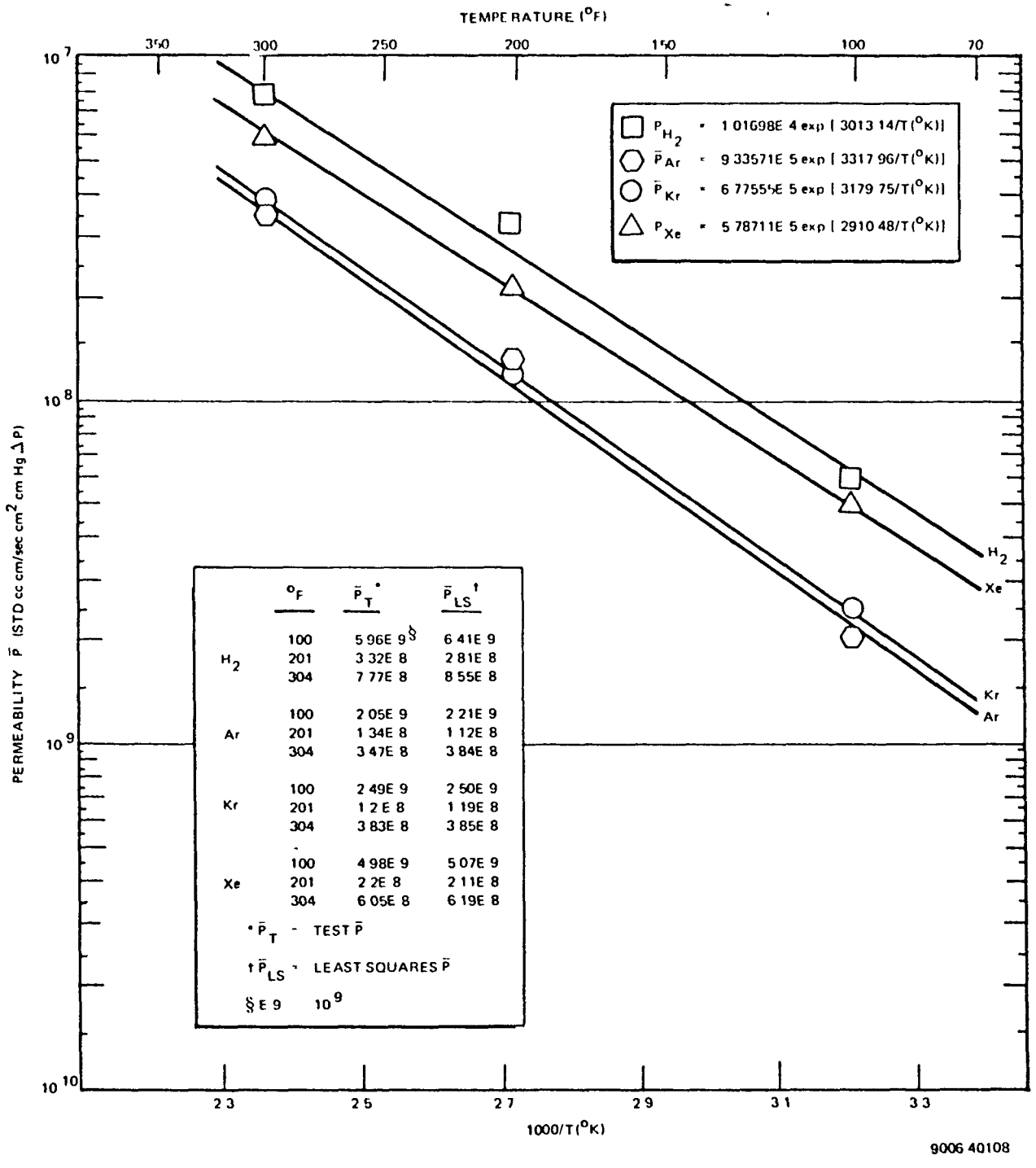


Figure 15. Log $\overline{P}$ vs 1/T(°K) for H_2, Ar, Kr, and Xe for Ethylene Propylene Rubber, Parker Seal Co., Compound E692

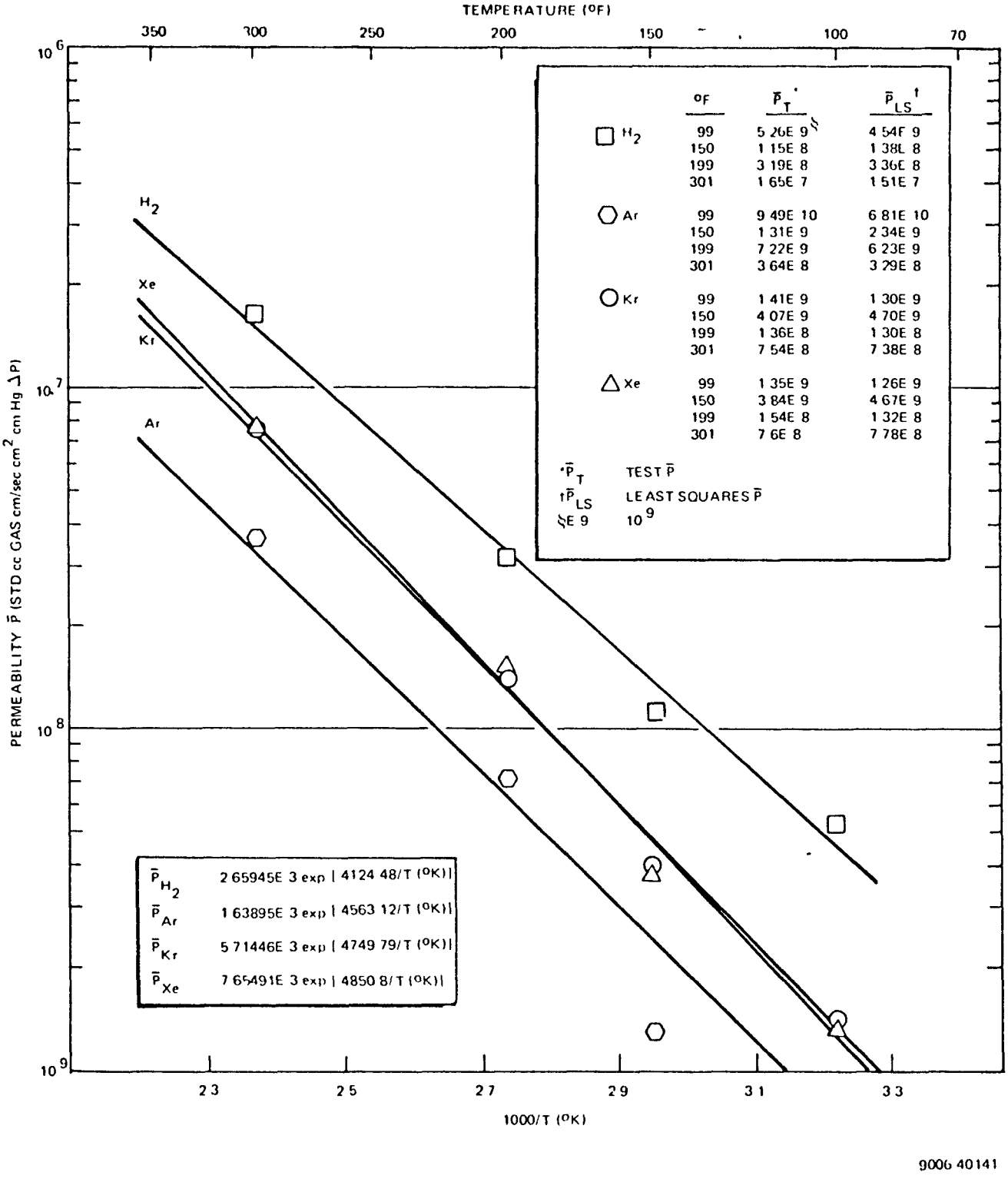


Figure 16. Log $\bar{P}$ vs 1/T (°K) for H_2, Ar, Kr, and Xe for Minnesota Rubber Polyacrylic (335GA)

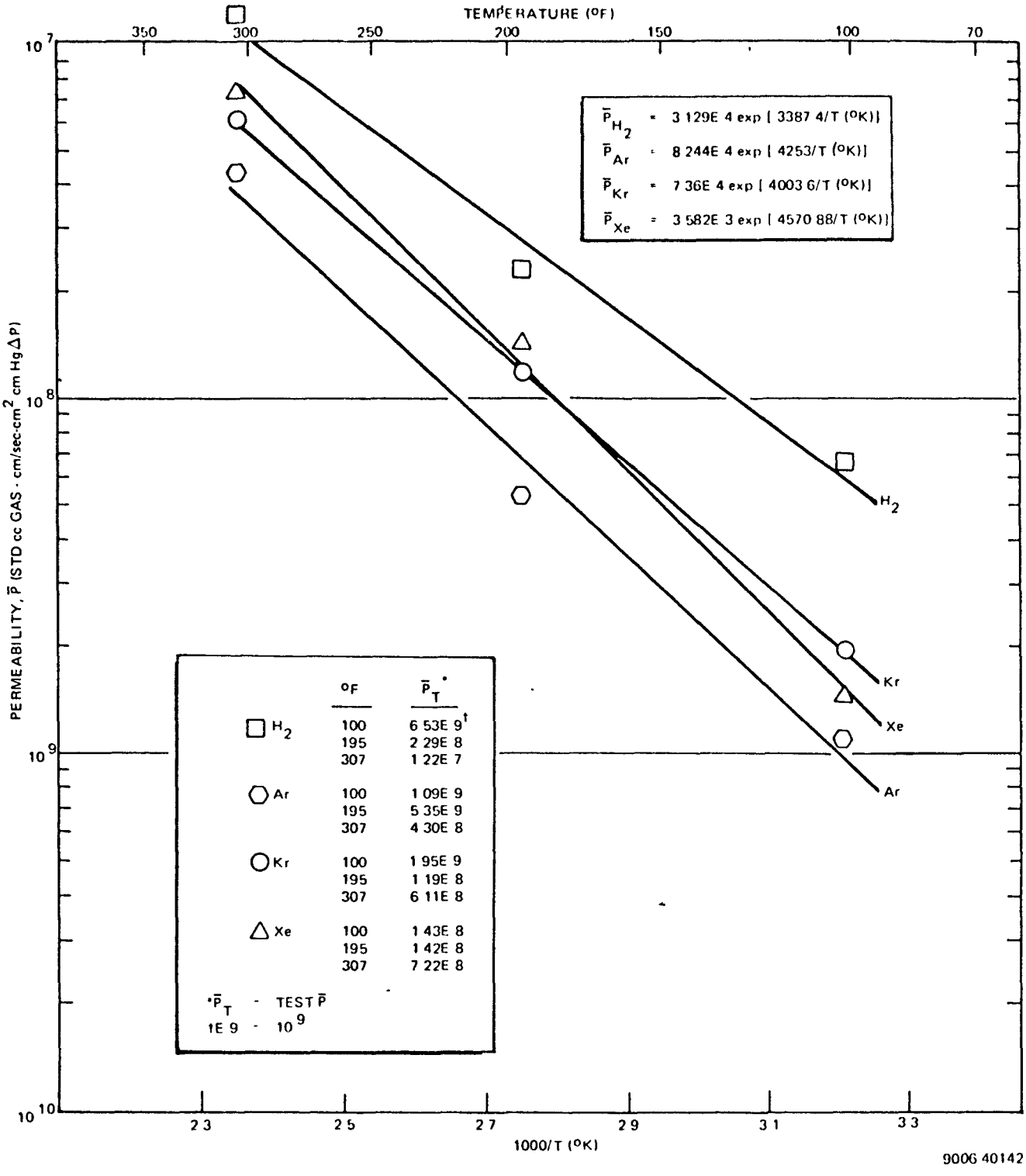


Figure 17. Log $\overline{P}$ vs 1/T (°K) for H_2, Ar, Kr, and Xe for Parker Seal Polyacrylic (A607)

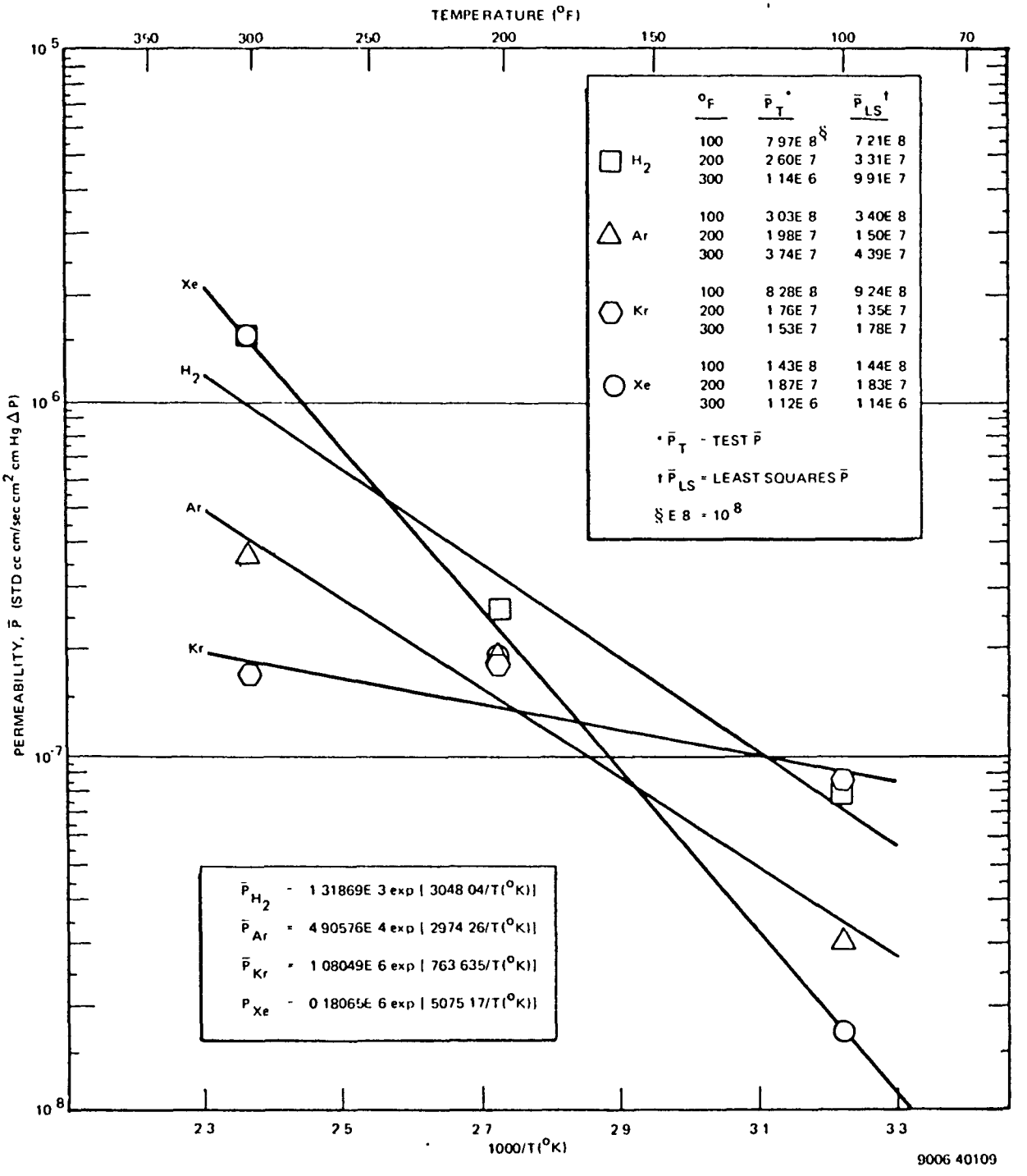


Figure 18. Log $\overline{P}$ vs 1/T(°K) for H_2, Ar, Kr, and Xe for Silicone Rubber, Greene-Tweed Co., Compound 407

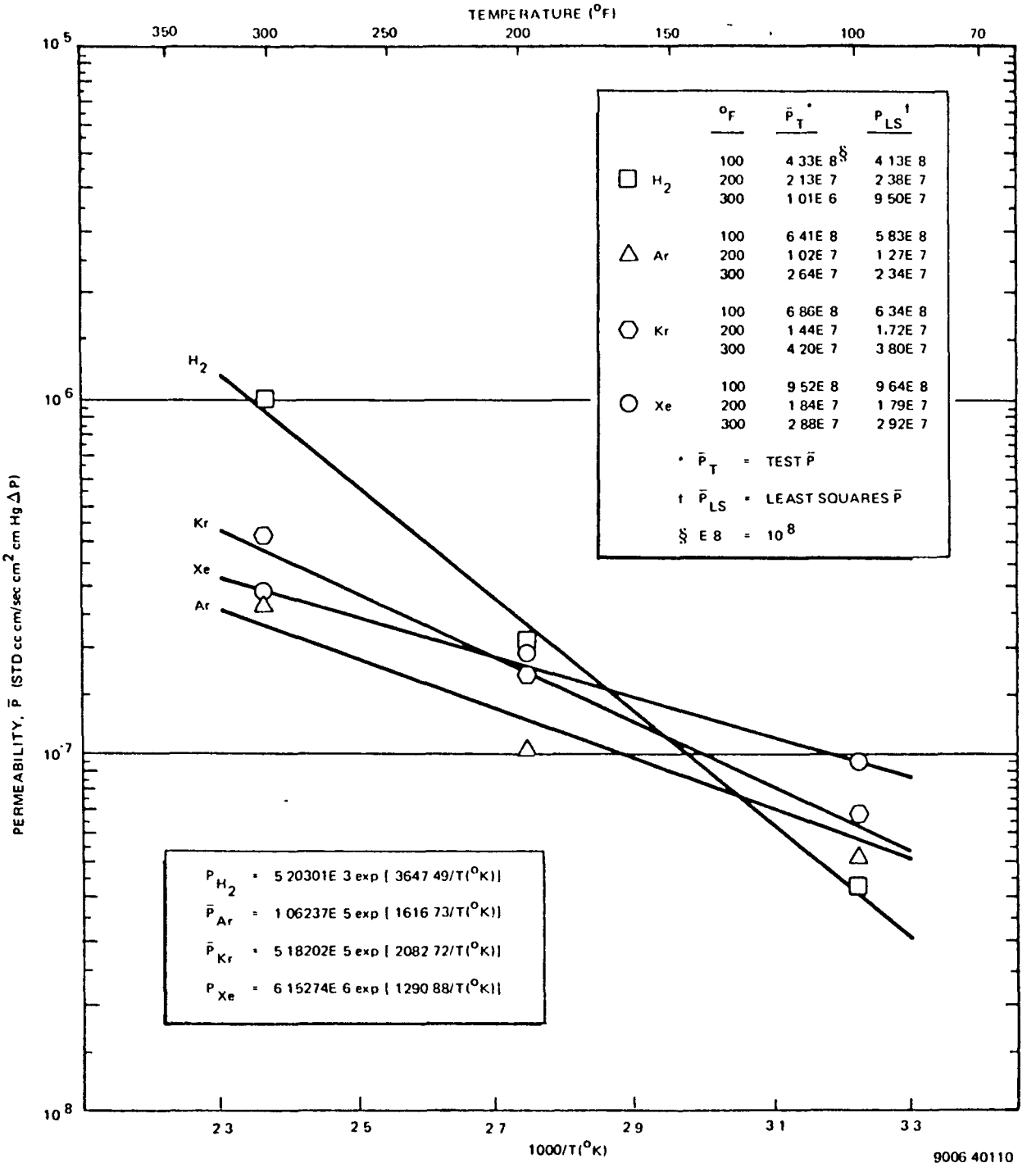


Figure 19. Log $\overline{P}$ vs 1/T(°K) for H_2, Ar, Kr, and Xe for Silicone Rubber Minnesota Rubber Co., Compound 71417

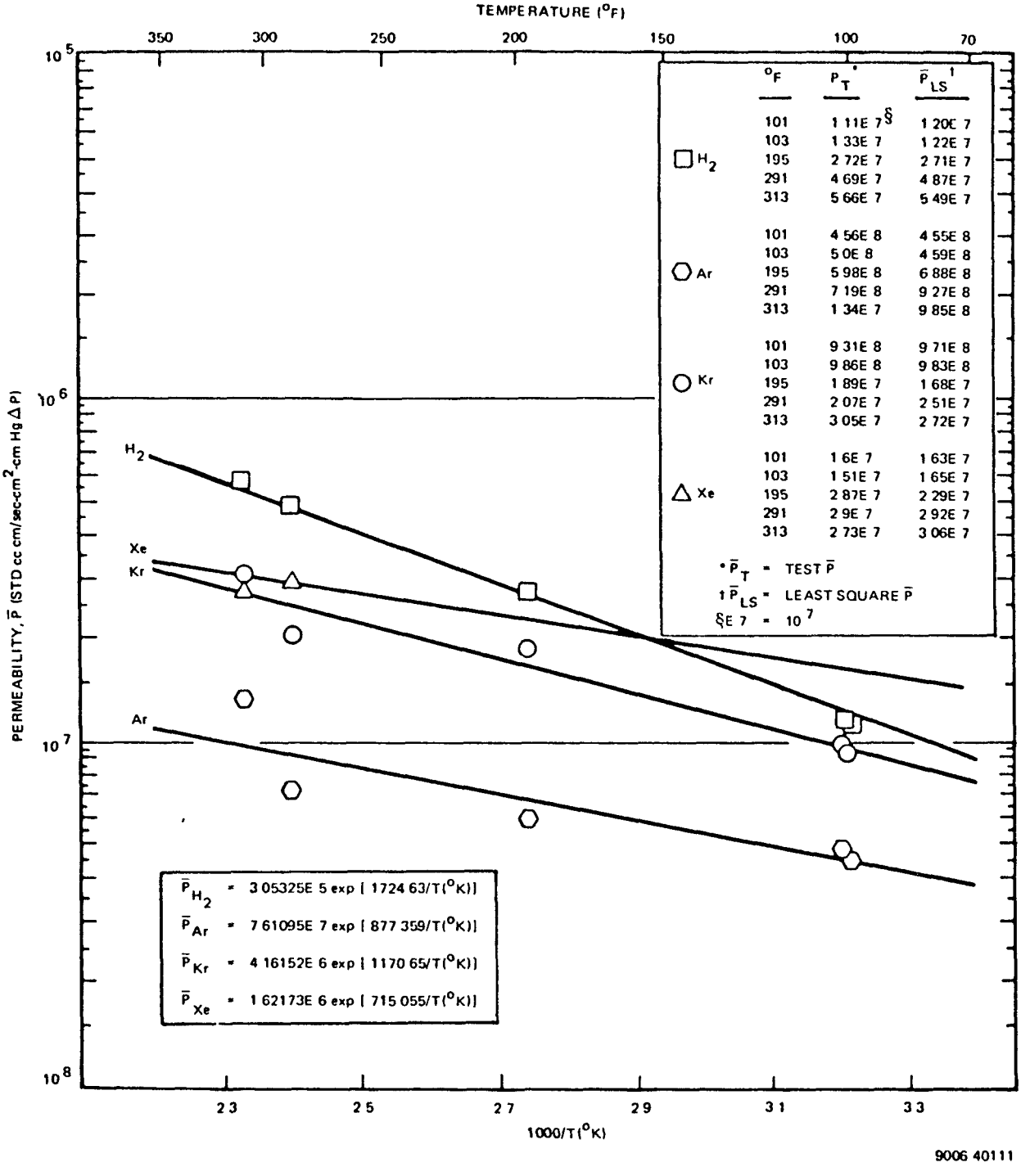
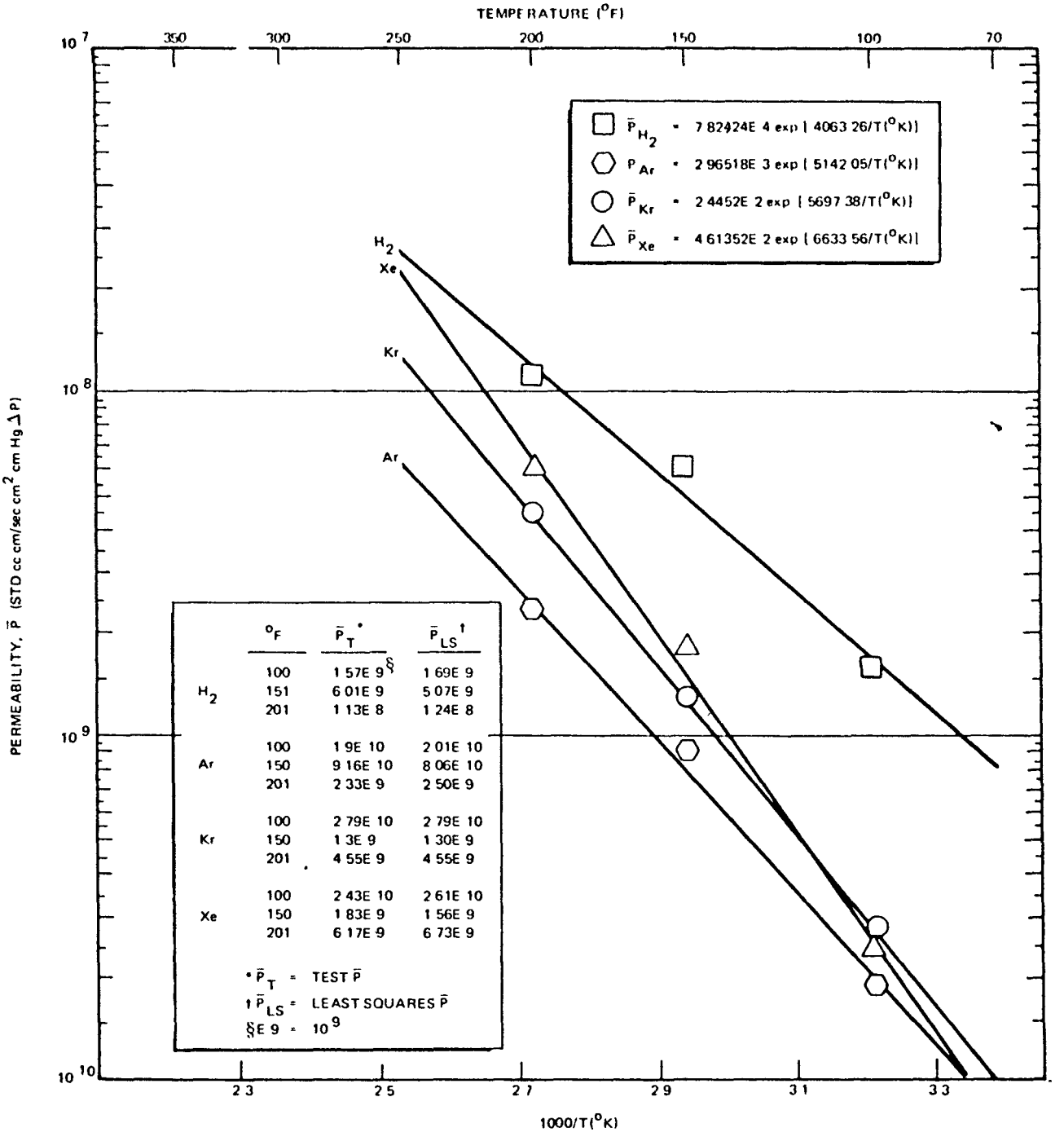


Figure 20. Log $\bar{P}$ vs 1/T(°K) for H_2, Ar, Kr, and Xe for Silicone Rubber, Parker Seal Co., Compound S684



	°F	$\bar{P}_T$*	$\bar{P}_{LS}$†
H_2	100	1 57E 9§	1 69E 9
	151	6 01E 9	5 07E 9
	201	1 13E 8	1 24E 8
Ar	100	1 9E 10	2 01E 10
	150	9 16E 10	8 06E 10
	201	2 33E 9	2 50E 9
Kr	100	2 79E 10	2 79E 10
	150	1 3E 9	1 30E 9
	201	4 55E 9	4 55E 9
Xe	100	2 43E 10	2 61E 10
	150	1 83E 9	1 56E 9
	201	6 17E 9	6 73E 9

*$\bar{P}_T$ = TEST $\bar{P}$
†$\bar{P}_{LS}$ = LEAST SQUARES $\bar{P}$
§E 9 = 10^9

9006 40103

Figure 21. Log $\bar{P}$ vs 1/T(°K) for H_2, Ar, Kr, and Xe for Urethane Rubber, Greene Tweed Co., Compound 379

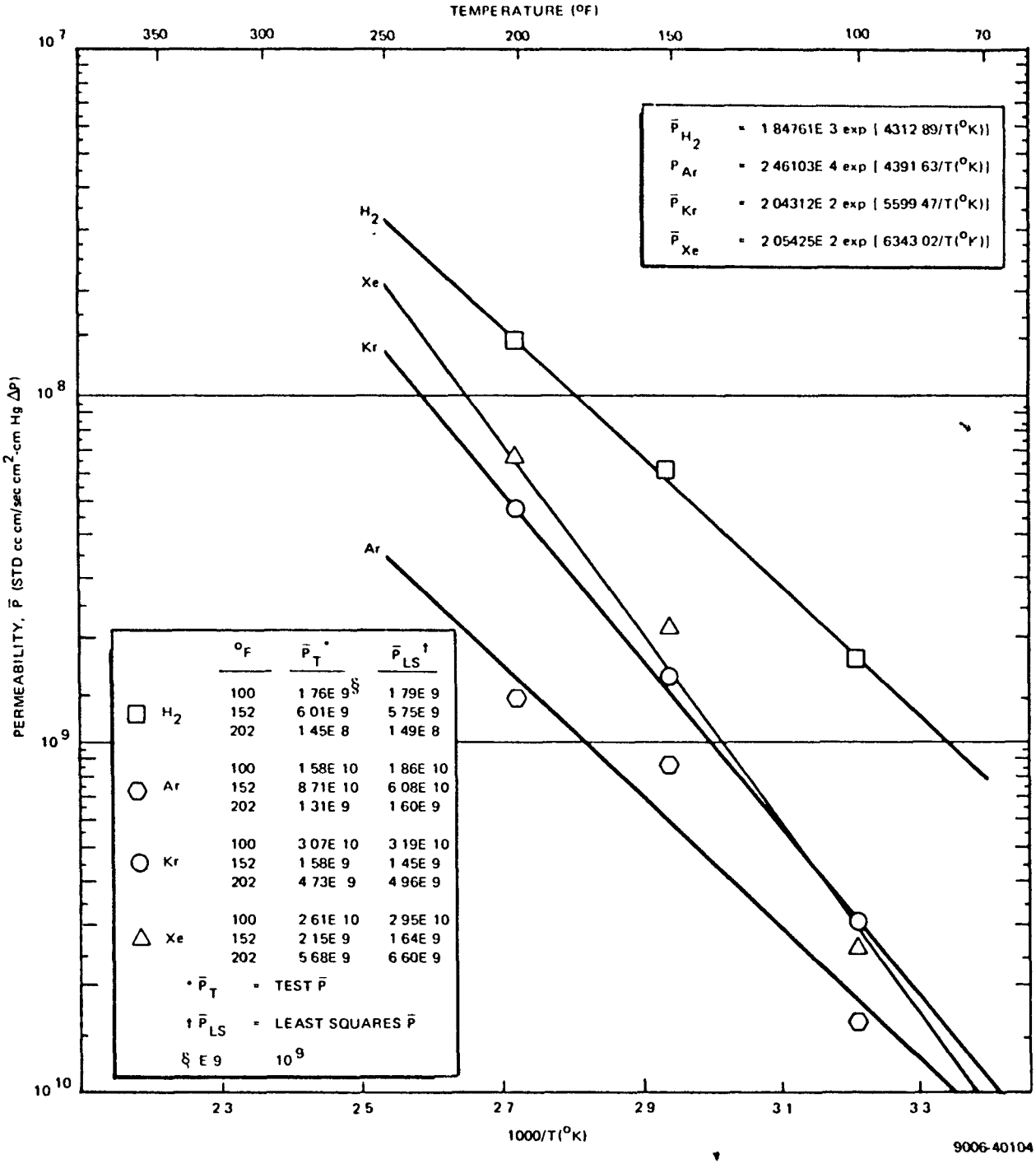


Figure 22. Log $\overline{P}$ vs 1/T(°K) for H_2, Ar, Kr, and Xe for Urethane Rubber Minnesota Rubber Co., Compound FX522

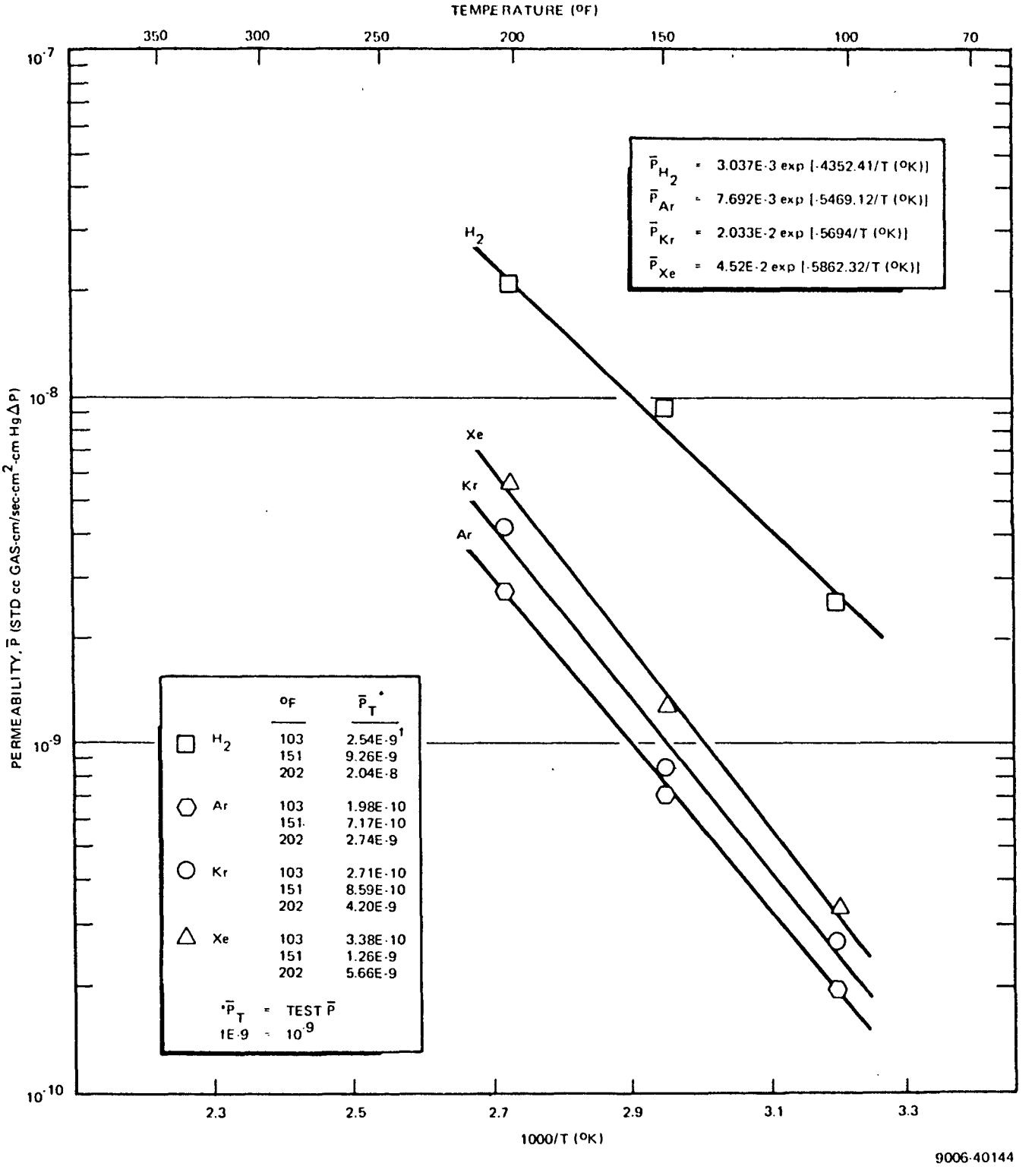
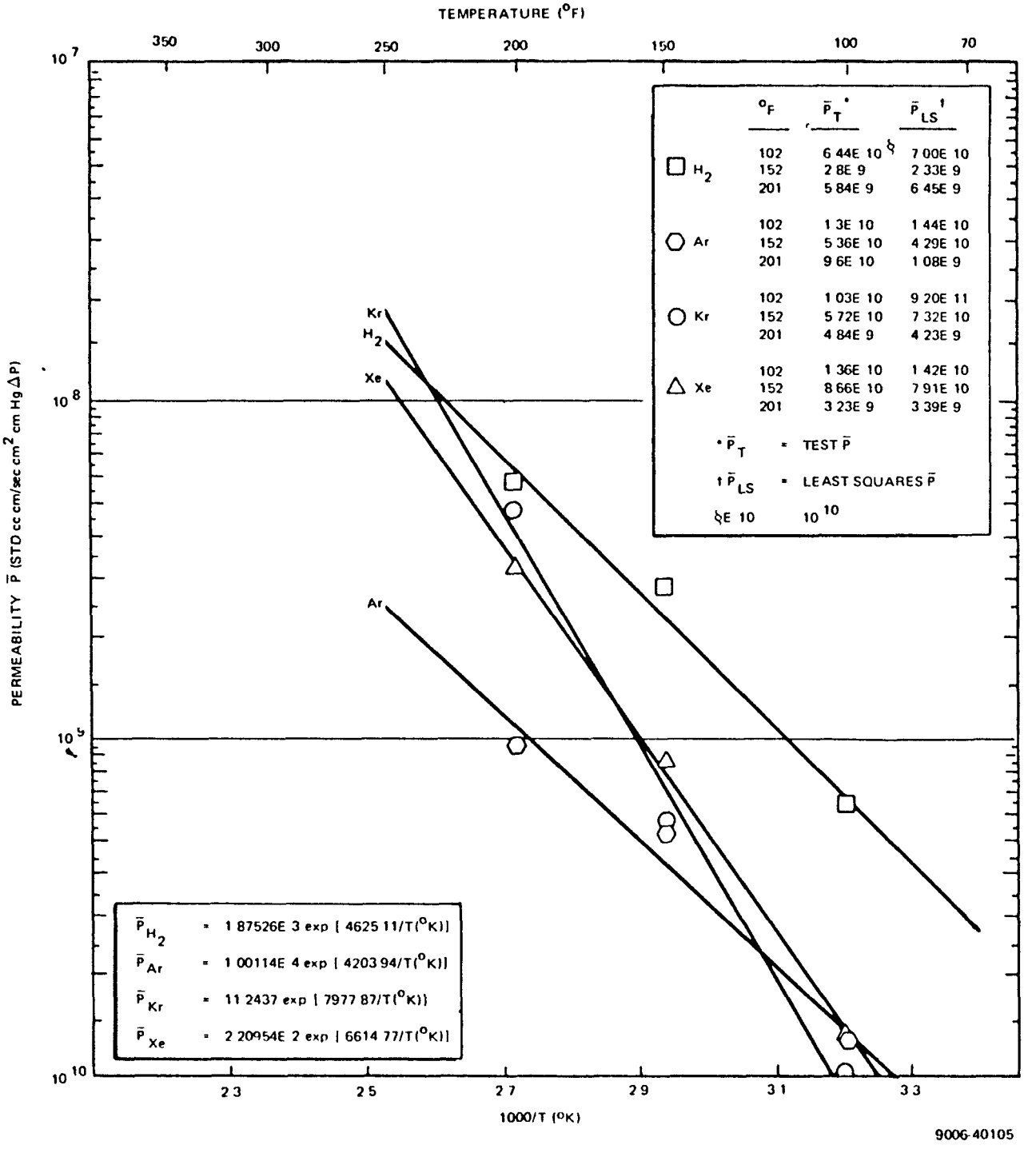


Figure 23. Log $\bar{P}$ vs 1/T (°K) for H_2, Ar, Kr, and Xe for Parker Seal Urethane (P642)



	°F	$\bar{P}_T$ *	$\bar{P}_{LS}$ †
H_2	102	6 44E 10 ◊	7 00E 10
	152	2 8E 9	2 33E 9
	201	5 84E 9	6 45E 9
Ar	102	1 3E 10	1 44E 10
	152	5 36E 10	4 29E 10
	201	9 6E 10	1 08E 9
Kr	102	1 03E 10	9 20E 11
	152	5 72E 10	7 32E 10
	201	4 84E 9	4 23E 9
Xe	102	1 36E 10	1 42E 10
	152	8 66E 10	7 91E 10
	201	3 23E 9	3 39E 9

* $\bar{P}_T$ = TEST $\bar{P}$

† $\bar{P}_{LS}$ = LEAST SQUARES $\bar{P}$

◊E 10 10^{10}

Figure 24. Log $\bar{P}$ vs 1/T(°K) for H_2, Ar, Kr, and Xe for Urethane Rubber, Parker Seal Co., Compound P648